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The Impact Response of Composite Materials Involved in Helicopter Vulnerability Assessment: Literature Review - Part 1

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ABSTRACT

The present review aims at a provision of scientific support to the introduction of the Tiger ARH (Armed Reconnaissance Helicopter) into service. The review examines more than five hundred recent publications on the impact response of composite and cellular materials which are constituents of modern air platforms, specifically, helicopters. Using the ARH in an operational environment makes ballistic damage assessment an important issue. This review focuses on the factors of material response associated with structure vulnerability, such as damage resistance and damage tolerance.

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Executive Summary

The present review examines studies of the impact response of composite and cellular materials. The review aims at the provision of scientific support for the introduction of the Tiger ARH (Armed Reconnaissance Helicopter) into service. Using the ARH in an operational environment makes ballistic damage assessment an important issue. In the majority of modern military air platforms, including helicopters, the skins, which protect vulnerable equipment and crew, are made of composite and cellular materials (the latter are also composites in a sense). Therefore, studies of the impact response of composite materials are particularly relevant to the helicopter vulnerability assessment.

An air platform's vulnerability is affected by both the structure design and properties of the materials forming the structure. The structure is vulnerable to loads before, during, and after an impact. The after-impact vulnerability also involves vulnerability of behind-skin equipment and crew. Therefore, evaluation of the reduction of a projectile's energy during penetration is one more aspect of the vulnerability assessment. A comprehensive assessment of the impact-related vulnerability also involves consideration of issues relating to an assessment of the ability of a damaged structure to be repaired and the structure vulnerability after the repair. Both these issues are identified in this review. Their detailed examination is, however, beyond the review scope.

This review consists of two Parts. Part 1 includes Sections 1-4. Section 1 formulates the purposes that governed this literature review and provides an outline of the paper. Section 2 focuses on structure certification and classification of threats; Section 3 – on material characterisation; and Section 4 – on general experimental techniques and theories used for studies of impact. Part 2 includes Sections 5-8. Section 5 reviews literature on damage response to low-velocity impact; Section 6 – on damage response to ballistic impact; and Section 7 – on after-impact evaluation characterised by damage tolerance and repair. Section 8, 'Conclusion' summarises trends and technology gaps in the area of impact response of composites.

Aircraft structure design imposes a number of restrictions on the properties of materials to be used. The restricting parameters could be seen as a subset of the design parameters. Formulation and establishment of the design parameters build up a process of certification. This process along with classification of threats is described in Section 2.

Characterisation of materials under loads before impact includes a determination of mechanical properties for static and dynamic conditions. This is a well-developed area of the mechanical engineering science. Typically the characterisation determines material's limiting stresses and strengths, including fracture onset. The methods that are applied to

conventional (metallic) materials can also be applied to the materials in modern helicopter structures. Section 3 outlines and examines the peculiarities of advanced material characterisation associated with anisotropy of materials and with strongly non-linear behaviour of foams. Non-destructive evaluation also deals with material characterisation from the viewpoint of the material quality and integrity. Relevant literature is reviewed in the last subsection of Section 3.

Material response to loads during impact is the most complex area of study, both theoretically and experimentally. The impact characterisation is not straightforward because it involves not only a determination of mechanical properties (such as the limit stresses and strengths at high strain rates) but also an analysis of the factors related to a large variety of the failure mechanisms sensitive to the impactor's characteristics such as shape and mass (which means sensitivity to the spatial and temporal distribution of the load). Also, the dynamic nature of the impact load should be taken into account, even for low-velocity impact. This rate sensitivity, having been noticed first in studies of conventional material response to impact, adds to the complexity of the advanced materials used in helicopter structures. Section 4 provides an overview of recent developments in this area.

Damage resistance and damage tolerance determine the skin capacity to reduce the impact threat. These factors relate to both the after-penetration energy of the impactor and the characterisation of the target response after impact. Damage resistance is an ability of the target material to resist the onset of damage and, thus, to protect the behind-target space against penetration of foreign objects. The material's protective properties against projectiles are characterised by the so-called 'ballistic limit'. The ballistic limit velocity is the most widely used characteristic of ballistic protection. It is linked with the energy that is absorbed by a target during a ballistic event. Damage tolerance is typically associated with the residual strength of the target material after impact. Material responds differently to low- and high-velocity impact threats. Section 5 provides an overview of studies of the damage tolerance at low-velocity impact (LVI). Issues of the ballistic damage resistance and tolerance are examined in Section 6.

The most dangerous mode of quasi-static loads to air structures susceptible to impact damage is believed to be compression. Therefore, a widely accepted characteristic of the damage tolerance is obtained with the Compression-After-Impact (CAI) test. This characteristic is called 'Compressive Strength After Impact' (CSAI). Publications focusing on the after-impact evaluation and on the after-impact repair of damaged structures are reviewed in Section 7.

Section 8, 'Conclusion', summarises the major issues and most relevant findings in the reviewed literature on composite and cellular material impact response. It also outlines current trends in theoretical and experimental studies of material characterisation for structures vulnerable to ballistic threats.

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Contents

1. Introduction

This report provides an assessment of the state of the art in studies of impact effects on composite materials. Such studies are highly relevant for an assessment of the vulnerability of air structures, and in particular air structures designed using advanced materials such as composites and cellular materials. Air structures, such as helicopters, are at risk of being damaged by high-velocity impact in a range of situations: from the effect of fragment impact during an attack with a warhead or bullet to the drop of a tool during an inspection/repair. The consequences of high-velocity impact vary from a Barely Visible Impact Damage (BVID) that may exhibit itself later on in flight, up to the fatal kill of the structure. Vulnerability of a helicopter structure depends upon both the design of the structure and loads applied to its elements.

Studies of high-velocity impact provide a necessary background for development of effective and efficient ways of assessing the capability/vulnerability of air structures used by Australian Defence Forces. These studies should inform DSTO's development of expertise in the area of helicopter structure response to impact and blast. The present report aims to contribute to DSTO's development of such an expertise and should be considered as a step in the development of a sound conceptual framework and reliable procedures for an assessment of the capability/vulnerability of air structures. The current report provides a detailed overview of contemporary studies in fields which are highly relevant for an assessment of the vulnerability of modern air structures to conventional and new types of threats. It offers a detailed analysis of the state of the art in this field, which can further inform development of practical recommendations and research in the impact/blast response of composite structures.

The report consists of eight sections; Section 1 outlines the topic, purpose, and the structure of this paper and Sections 2-7 provide reviews of the literature on specific issues.

The skin of many military air structures is made of composites or other advanced materials. Studies of composite material response to impact are becoming more important due to the wide usage of composite materials in air structures. It is not easy to identify damage in such materials because of their structural complexity. A structure must be certified to determine the loads that can be carried. A variety of damage types, which can occur due to a manufacturing process, exploitation, or external threats, can degrade the mechanical properties of materials, and makes it necessary to define the damage tolerance as part of the certification. Traditionally, conventional metallic materials were used in air structures and the components of the air-structures and sub-structures were tested in full-scale as part of the certification process. Such full-scale tests are no longer the most cost efficient way of assessing air structures in terms of their vulnerability, due mainly to the use of advanced materials (composites, foams etc) that are characterised by more diverse and complex responses to threats. This diversity and complexity requires the use of more thorough and sophisticated testing methods, tools, and procedures than those that can be provided in 'real', full-scale testing. In addition, the increasing number and constantly changing character of threats (and, in particular, a growing trend to use unconventional threats quite creatively) make vulnerability assessment with full-scale testing practically impossible. Section 2 outlines procedures of certification and possible threats to structures that are considered in literature.

Load allowables derived during the procedure of structure certification are determined by the mechanical characteristics of materials. Section 3 provides a review of studies which focus on the material characterisation of composites. The principal characteristics of the materials used in air structure design are: the material's ultimate stresses and strains, such as the yield and strength limits at prescribed simple or complex stress states in static or high strain-rate conditions (for example, the elastic limit measured with static testing machines and the yield stress obtained with a variety of testing devices in the dynamic conditions), the failure strain and fatigue limit stress. Testing of composites frequently involves a failure of structural materials. This means that the composite's mechanical properties obtained in testing are inextricably associated with the failure mechanisms of the materials being tested or exploited. This makes characterisation of composite materials an extremely complex area which, nevertheless, is being intensively developed at present because of the wide usage of composites in military, industry and civilian applications. Advanced characterisation of composite materials includes: 1) limit strains at specified conditions of loading and testing (such as ultimate deformation with Charpy testing); 2) ultimate limits of energy at fracture (such as the fracture toughness – energy required to fracture material); and 3) limit stress for irreversible changes in materials (the Hugoniot limit in plane wave testing).

The damage resistance linked with dynamic behaviour also relates to the after-impact characterisation via the energy absorbed by a target during the impact event. Skin integrity may be vital to the integrity of the structure. Therefore, after-impact analysis is a key element of the vulnerability analysis as it provides crucial data on the damage tolerance. Due to the possibility of internal damage, such as delamination or the behind-skin structural damage in cellular materials, visual inspection cannot help estimate the full extent of the damage from ballistic impact. Internal damage can be estimated with 'destructive' methods, such as cross sectioning followed by optical scanning. It can also be estimated with Non-Destructive Evaluation (NDE) methods, such as acoustic scanning and X-ray inspection. The NDE methods are rapidly expanding and are being used extensively and intensively in material characterisation. In Section 3 of this report, the most extensively used NDE methods are outlined and analysed in terms of their reliability and heuristic significance to impact response studies.

Structures respond to threats (static loads, impact, fatigue) in different ways depending on the energy and concentration of a load. In this report, we review studies of composite and cellular material response to both low- and high-velocity impacts. In the literature, target failure responses under dynamic conditions are examined from both theoretical and experimental viewpoints. This examination includes detailed evaluation of the target response based on progressive failure and constitutive behaviour of the target material and an integral evaluation linked with the ballistic limit velocity as a measure of the damage resistance. The target's damage resistance, which indicates the material's capacity to resist the impact, is directly linked with the behaviour of the target material and with the target's response during the impact event. The damage resistance is linked with the energy absorbed by the target during the ballistic impact; a complex process even for isotropic materials such as aluminium or titanium and even more complex for anisotropic materials (composites). Section 4 outlines novel experimental methods of damage evaluation during impact, focusing on the methods developed for evaluation of composite damage.

Procedures for ballistic impact testing in laboratory conditions (including requirements for the shape of a projectile, conditions of the encounter, etc) and interpretation of the results are well documented (see, for example, military standards). However, in real-life situations, the impact process almost never happens in the conditions prescribed by the standards. In real-life situations, the impact process is complicated by static or transient loads pre-applied to the target, non-ideal conditions of an encounter, structural and variable ambient environment. All of these factors make impact response simulation a complex problem. The complexity is reflected by a diversity of modelling approaches employed in studies of the damage response of composites and other structural materials. Modelling requires detailed information about material properties, including data on yield stress and strength at various loading modes, failure thresholds, etc. These data can be obtained via material characterisation tests under static and dynamic conditions (these conditions are described in Section 3). The impact response is usually analysed with structural or constitutive modelling performed either by finite-element-analysis (FEA) programs or by hydrocodes. Section 4 provides an overview of the modelling techniques and models used for a numerical analysis of the impact events.

Section 5 focuses on studies that aim at an assessment of the residual strength of materials. Such an assessment involves a variety of after-impact examinations, such as Tensile-tests, Flexure-tests, Shear-tests, and the Compression-After-Impact (CAI) tests. Because composite materials have the highest sensitivity to compression after impact, the CAI tests prevail in the majority of the studies. In ductile materials, such as alloys, reduction of the strength to the Compressive Strength After-Impact (CSAI) is caused mainly by propagation of cracks generated due to the impact. In composite materials, reduction in the CSAI (for the majority of cases reported in the literature) is caused by internal in-plane delamination of the materials due to the impact. The delamination area is sometimes used as an indirect parameter for evaluation of the CSAI. The after-impact characteristics are usually predicted with a variety of empirically based semi-analytical techniques. Analytical and numerical methods for the after-impact assessment of residual mechanical properties are currently being developed and employed along with methods for an assessment of a repaired structure. Section 5 outlines the state of the art research in this area.

Section 6 examines studies in the area of damage resistance evaluation and reviews models predicting the behind-target energy of the projectile. The damage resistance at ballistic impact (the ballistic resistance) can be evaluated through the ballistic limit velocity

(V50) for a given combination of projectile and target. The damage resistance is associated with the absorbed energy and is indirectly linked with the residual kinetic energy of the debris or the projectile behind the target (skin). Therefore, information on the residual energy is important for an assessment of the vulnerability of the crew, vital equipment, and other secondary behind-skin targets.

The after-impact characterisation of a target due to ballistic impact is considered in Section 7. The most important after-impact characteristics are damage resistance and damage tolerance. Damage resistance and damage tolerance are concepts that are inseparable from each other. Damage resistance characterises the amount and type (spatial and temporal concentration) of energy that a target may sustain (presumably, to preserve its bearing capacity). Damage tolerance characterises the target's after-impact bearing capacity. The material's damage tolerance is related to its capacity to retain structural functionality under static or dynamic loads (e.g., the capacity to sustain multiple ballistic impacts). The damage tolerance is associated with the residual strengths, modulii, and other after-impact residual mechanical properties of the target material. The residual characteristics of a composite skin are important for operational evaluations, e.g., for evaluation of the possibility of mission continuation or for evaluation of survivability.

The primary characteristics of damage tolerance are obtained with Compression After Impact (CAI) tests. Methods of CAI inspection after a ballistic impact and after a low velocity impact are basically the same. The impact response of complex structural materials, such as composites, is more complex than for metals, because complex material response is linked closely with such factors as environmental conditions and the way in which the material was manufactured. Due to the multiplicity of factors which may influence a complex material's response, methods of characterisation of damage resistance and tolerance are still developing. Section 7 outlines the most significant attempts made in this direction.

Section 7 also provides an overview of the literature that focuses on the important issue of improvement of air structure damage tolerance. The damage tolerance of structure components subject to impact in battlefield conditions can be improved with battle damage repair (BDR). In order to know how urgently a repair should be performed and how reliable the air structure is after repair, it is necessary to develop rigorous and reliable procedures of repair certification and assessment. Section 7 briefly outlines the procedures reported in the literature on repair certification and assessment.

The conclusion provides a summary of the main points made in the literature review and emphasises the importance of the examined areas (experimental and modelling approaches in studies of composite materials' response to impact) for an assessment of air structures' vulnerability in conflicts and peacekeeping missions. Also, the conclusion links this review with the Battle Damage Repair program and vulnerability of the helicopter platform and identifies those elements of the WSD R&D program that can be usefully informed by the analysis offered in this review.

2. Structure certification and threats

2.1 Certification of structure

Components of an aircraft structure have different vulnerabilities to external threats and secondary structure loads. This means that if an equivalent damage level is applied to different components, they will have different tolerances to specified loads depending on their functional roles. Therefore, components should be assessed individually, which is done through the process of certification.

Certification is an important step of structure design. The certification procedure is illustrated in the present report with several examples outlining the place of component damage and its assessment within the process of certification and showing how the certification relates to the vulnerability assessment. The damage assessment attributed to specified loads is particularly important for a composite-containing air-structure because of its sensitivity to impact and because the composite parts exhibit anisotropic response to loads. This is specifically relevant to the TIGER helicopter as a representative of the Eurocopter family of rotorcraft machines. For example, the main material in the NH90 fuselage is carbon fibre composite. Aramid fibre composite is used in lower parts of the fuselage to optimise the crash behaviour and glass fibre composite sandwiching a Nomex core is used in secondary structures of NH90 (see [Torres, 1995]). Generally, structural components are grouped into three large families by the criticality to safety as primary, secondary, and tertiary structures as described in paper [Baker, 1997].

Certification is a multi-stage process. It includes: i) selection of materials that suit the design purposes; ii) qualification of the material and process; iii) development and qualification of design allowables (e.g., strength and failure strain); iv) evaluation of the allowables via coupon testing. The four stages include qualification and evaluation of allowables at different specified conditions similar to the real conditions in which the structure is operating. It should be mentioned that coupon testing is typically a quite extended stage of the evaluation. For example, coupon tests, which were listed in paper [Adams, 1995] and required by a military standard, include tension and compression tests for laminates in two perpendicular directions, in-plane shear tests, and short beam shear tests; these tests are conducted in different moisture and temperature conditions. Illustrating influence of the environmental conditions, composites exposed to high humidity and high temperature conditions for a long time absorb moisture, which degrades the composite matrix and affects the allowables.

An example of the allowables selection and a testing program for the four substages, including the test matrix at different loading and environmental conditions, has been demonstrated in paper [Sawicki, 1995] for the Engineering and Manufacturing Development program of the V-22 US Navy helicopter when the graphite/epoxy tows replace the fabric system of the fuselage. Certification of such a component as a bay door of the AH-64D Apache helicopter when replacing standard thermoset composites with thermoplastic composites (which results in substantial cost savings) has been conducted in paper [Jouin, 1998]. A study for redesigning and certifying the wing drive shaft for V-22 helicopter subject to new requirements and advancing further into a full-scale FE modelling and testing is reported in paper [Komenda, 1995].

The certification process is finalised with: v) sub-component; vi) component; and vii) full scale testing (some guidelines precede sub-component with element testing). A list of criteria being applied to the development of allowables and sets of tests towards structural substantiation through this certification chain is demonstrated in paper [Adams, 1995] for the US composite-containing helicopters MD-900, V-22, RAH-66 (Comanche) and K-Max. An example of the certification approach for the European EH-101 helicopter, which is applied to such primary composite-containing structures as the Main Rotor Hub, the Tail Rotor Hub and Blade, the Tail Unit, and the Flight Control Rods, is described in paper [Guzzetti, 1995]. The process covers evaluation of a range of environmental effects, impact damage, and lightning strike. Paper [Guzzetti, 1995] outlines the connections of coupon testing with structural substantiation via the full-scale testing of the helicopter units.

The design requirements of an air platform are determined by parameters regulating factors of safety. For air structures it is common to operate with the Design Limit Load (DLL). The DLL is a basic point for various criteria of safety including the Design Ultimate Load (DUL) that is usually 1.5 ·DLL. The reserve factor f (for instance, for the DUL this factor is usually 1.5) determines the Margin of Safety (MS = f – 1). Evolution of the margins of safety, when a CH-47 helicopter structure is subject to a damage scenario, has been illustrated in paper [Berczynski, 1998] using a finite element (FE) simulation. The design process involves analysis and testing verification, which are used for determining the DUL and MS with the purpose to establish: (a) the accuracy of loading (Flight Testing) and (b) the accuracy of structural design and confirmation of failure modes (Structural Testing). This approach has been used for certification of the composite material components of the MD900 Helicopter in paper [Dutton, 1997].

Paper [Vijayakumar, 2004] provides an example of establishing the design allowables for an element of structure (sandwich composite cylinder) by conducting a parametric study, when parameters of the cylinder (ply sequence, etc) are selected as the parameters to be varied. Evolution of the material parameters bounded by the design allowables, when a component has been damaged or a weakness such as an initial hole has been introduced, was analysed in paper [Wang, 2004a] using the progressive failure approach and an elastic modulus as a fitting parameter.

Monitoring the change of design allowables similar to that used in a structure with a patch repair (see [Baker, 2004]) is an important area of health structure studies. Straightforward health monitoring may trace current strain. More sophisticated analysis may involve tracking of crack density in a composite matrix with Bragg grating sensors. A paper by [Pawar, 2005] proposes an algorithm for handling such data for a composite rotor blade and a methodology for analysis of fatigue life (frequency response) when matrix cracking is developing. This paper also explores the inverse analysis from the strain data obtained. Usually designers lack data for various situations in which the structure can or may be used. To assist in this it is particularly useful to investigate cases which can determine the allowable range of the reserve factor in order to use the benefits of light-weight material. For example, papers [Roach, 1998a; Roach, 1998b] consider sandwich single-skin structures and estimate the reserve factor from the static test fracture data. This allows an evaluation of the impact penetration energy.

When moving to a next structural level, joined elements of a structure are to be tested, enabling one to determine the design allowables for such parts as bonded-bolted and co-infused sandwich composite/steel joints (see [Cao, 2004]) and accordinly the selection of appropriate design allowables. In the paper [Cao, 2004], the procedure of allowables determination includes tensile tests and three-point bending tests that enable the designer to deduce relevant strengths. Detailed FE modelling was conducted in paper [Cesnik, 1995] for rotor blade cross-sectional analysis. This FE analysis is within the anisotropic elasticity approach, which is proposed as a general framework for composite beam modelling by rotor blade designers. A higher level of detail is involved in sub-component testing and modelling. For example, when quality of repair and the response of subcomponents and structure to loads are being assessed, traditional finite element modelling, which operates with structural stiffness and the load-to-displacement response, is gradually being replaced with detailed modelling based on the constitutive response of the structure elements (see [Jones, 2004]).

Data obtained from highly detailed analysis and tests allows assessment of substructure at a higher level. Paper [McCarthy, 2000] demonstrates the design of an energy-absorbing subfloor structure made of composites under a design-for-crash-survivability (CRASURV) research programme. A numerical methodology based on a PAM-CRASH finite element code along with the low velocity impact (LVI) tests is explored in papers [Kohlgrüber, 1998; McCarthy, 2000]. It should be noted that the numerical model used for an absorbing structure containing porous materials, treats the porous material as a conventional materials simple by changing the material's elastic and shear properties at compaction. Although discrepancies between the tests and calculation are seen to be fairly significant (from 70 to 100%) and the numerical model is obviously oversimplified, the positive outcome is that substructure testing and design have been conducted in full for an aircraft substructure.

A low level approach that directly relates material properties with the certification process is the design of materials with desirable characteristics. This approach deals with composites and even more complex structural materials, which are used in the design of helicopters, such as sandwich structures containing cellular materials. Manufacturing strategies in order to reach desirable properties for cellular materials have been considered in paper [Wadley, 2002].

A somewhat inverse approach to the safety issue is also being explored, which is the design of sacrificial structures that are supposed to crush and absorb as much energy as possible in order to protect the crew and other vital parts of the structure. An example of such a study associated with a composite part of a sport automobile is described in paper [Savage, 2004]. Nevertheless, traditional approaches, such as selecting input parameters (design allowables) and defining a methodology to specify a design aiming at the minimization of the probability of failure of a composite structure at impact, as described in [Guillaumat, 2005], are prevailing. It should be noted that the choice of parameters, which has been done in the study [Guillaumat, 2005], is somewhat questionable because the parameters selected are not fully independent; for example, this set contains interrelated parameters such as the difference between impact and rebound velocities and the dissipated energy.

From the certification viewpoint, assessment of the vulnerability of a structure, which has been damaged at impact or/and repaired after the impact, is an investigation of how material characteristics (after the damage or repair) fit into the design allowables domain and whether those characteristics are within the safety limits. Monitoring the repair and keeping the parameters within the safety limits is one of the contemporary issues in the area of structure control within certification guidelines (see [Baker, 2004]). This health monitoring technique involves novel instrumentation via the smart materials approach as well as novel gauge instrumentation, making the system respond with instrumented notification if the material characteristics are out of the safety range (see [De Oliveira, 2004; Rosalie, 2004]).

Full-scale experiments are expensive; therefore studies aimed at understanding which physical processes control a number of critical situations are very important. These studies allow researchers to reveal specific processes that can be investigated in detail under laboratory conditions (see [Found, 2005] for an analysis of the characteristic failure modes occurring during impact in a composite-based sub-structure). Due to the lack of published data, when assessing the effect of impact, we will primarily be reviewing the structure response at the material response level and, briefly, the impact response of joints.

2.2 Threats to helicopter structure

Threats differ by the amplitude and spatial/temporal distribution of energy (the latter characterises the energy concentration) deposited in a structure via a threat. For example, typical fatigue loads are at low concentration and amplitude but, having been repeated many times, they can cause threatening damage. However, the present review is primarily focused on isolated impact loads.

A structure may face various threats with extremely concentrated loads including hypervelocity impact loads due to kinetic energy projectiles and fragments from high explosive warheads, as well as jets from shaped charge warheads. The hypervelocity range threats are more likely in well-developed conflicts. In local conflicts and peacekeeping missions ballistic threats are more likely, including bullets, armour piecing projectiles from hand weapons, and incendiary high explosive projectiles from shoulder weapons.

Typical examples of ballistic range threats are small calibre projectiles (for example, 5.56-mm blunt and armour piercing (AP) projectiles and 7.62-mm AP projectiles) and large calibre projectiles such as 12.7-mm and 14.5-mm AP projectiles. For example, vulnerability to 12.7-mm impact was among specific military constraints for design of the fuselage of the NH90 Eurocopter analysed in paper [Torres, 1995], and 20-mm and 23-mm armour piercing incendiary (API) and high explosive incendiary (HEI) projectiles were threats in the analyses conducted in papers [Anderson Jr., 1999a; Crawford, 1994]. HEI ammunition presents a more complex threat because the HEI threats combine a high concentration of impact energy with less concentrated (but wider distributed spatially) energy due to the detonation of the high explosive. Papers [Caravasos, 1998; Orlino, 1995a] consider design issues associated with HEI and Slewed Beam Laser threats against a tailboom composite structure in conditions that are applicable to RAH-66 Comanche helicopter structural loads.

In relation to composite targets, typical ballistic projectiles do not deform significantly. Therefore, the key characteristics of the threats in the case of ballistic impact are usually considered to be the nose shape of the projectile as well as its diameter and mass. Occasionally, the length of the projectile may play a role. However, the design of skins with higher protective capacity, such as metallic foams and sandwich skins, may involve more complex considerations, including consideration of the deformation of a projectile and formation of secondary debris.

Low energy impacts are also ballistic threats. For example, secondary fragments such as ricochet projectiles, and even stones or inspection/repair tools hitting helicopter skin can be classified as low-energy/low-velocity threats. Although damage from low energy impact is not always visible, it is important to realise how this damage could influence the performance of the skin and its susceptibility to subsequent higher energy threats or to structural loads.

Low energy impact threats to air structures are numerous. As an example the following threats have been considered in the literature: stones from runway or landing area [Grant, 1998]; bird ingestion into an air engine [Sun, 1975]; direct hit by bird on the structure components [Ruiz, 1994; Ruiz, 1998]; low-energy impact by ice particles [Kim, 1997]; and the occasional dropping of a tool. Less concentrated threats, such as those from the products of blast [Wierzbicki, 1999], are also possible from the use of energetic or explosive devices (e.g., firing a missile from a man portable weapon such as MANPAD) in the vicinity of a helicopter structure.

Studies of the synergy of blast and fragmentation effects on targets are becoming particularly important because of the development and proliferation of novel weapons for missiles, HEI projectiles, etc. For example, studies of the blast-fragmentation effects against targets made of conventional materials have been conducted in papers [Resnyansky, 2002a; Resnyansky, 2004a]. Design of specified composite barriers for Comanche and Apache helicopters against blast/fragmentation threats have been examined in paper [Huyett, 1995]. Some studies show that the blast and associated elevated pressure loads which are caused by the helicopter's own weapon hardware should be assessed as a threat to the helicopter structure. For example, design of a composite door analysed in paper [Jouin, 1998] takes into account the door's material resistance to blast pressure when firing Hellfire. The AH-64D Apache helicopter structure subject to the blast effects from a 30mm chain gun is evaluated in paper [McCarthy, 1998].

3. Material characterisation - Split Hopkinson Bar testing

3.1 General methods of material testing

Traditionally material response to small and moderate deformations is associated with material bulk and shear resistances under strain loading. Therefore, material characterisation in the present Section is considered as the determination of the material's stress/strain response which defines the material resistance to deformation. Resistance of conventional materials is usually more sensitive to shear loading than to other modes of deformation. As a result, when testing solids, arrangement and analysis of the uniaxial stress condition are of primary interest to experimentalists because this condition provides a material's shear response information. Traditional design allowables for uniaxial stress conditions might be elastic modulii, elastic limit, yield (plastic) limit, and the strength of the material. Traditionally, the material response in testing machines is considered to be dependant on the material displacement (sample elongation/contraction) caused by a load when deforming the material; which takes the form of a stress-strain curve. The stress-strain curve is the key information for the design process and the stress-strain dependence is a principal input for material models employed by finite-element programs and hydrocodes.

In comparison to conventional metallic materials, a characteristic feature of composite and honeycomb materials is their strong directional anisotropy associated with large variability of the mechanical properties of its constituents. Therefore, every experimental stress-strain curve for these materials is closely associated with the load direction with respect to the material symmetry axes. Under static conditions, stress-strain curves are routinely obtained with tensile testing machines. For example, tensile testing of a carbon-fibre composite at two very low strain-rates has been conducted in paper [Masuko, 2004]. In those tests a two-branch 'hardening' shape of the curve is seen, which has been predicted in paper [Resnyansky, 1997a], as a general feature of two-constituent composites loaded along the symmetry axis. The purpose of the paper [Masuko, 2004] was to assess the limit stress at an elevated temperature (100° C for several hours) that resulted in stress relaxation and reduction of the limit stress. In the study [Masuko, 2004] the limit stress was observed to be constant at a pre-selected temperature.

Load-displacement curves for composites, which are used either for derivation of stress-strain curves or for calculation of integrals associated with the energy absorbed by the material, are typically obtained from records taken at the crossheads of testing machines (loading cell data and crosshead displacement). These data may not reflect the sample's state precisely enough because the records at the crosshead and loading cell show averaged response of the testing machine to deformation of a sample made of an advanced material. Therefore, more direct methods such as the monitoring of the sample's state with strain gauges are commonly used. Other less intrusive novel methods have recently been developed (see [Yao, 2003]) based on the use of optical sensors to allow tracing of the extension of an undamaged or notched sample.

Traditional testing methods (methods that record the stress-strain response directly) are employed in quasi-static conditions. Nevertheless, materials may exhibit dynamic behaviour, for example in the form of material instability under compression (buckling) or crack propagation associated with loss of strength under shear or tension. The energy release rate with crack propagation is also considered to be a characteristic of a material. The strength effects which are associated with cracking are related to specific fracture modes and might be expressed via the energy release rates.

Traditional methods of evaluation of energy release rates are wide-spread. For example, paper [Chaturvedi, 1985] surveys methods of fracture characterization in composites. In this paper, the following three basic test approaches to characterisation are emphasised: i) load-displacement records for notched specimens with different crack length; ii) crack growth resistance measurements; and iii) measurement of the area under the load-displacements curves to assess the work of fracture. These methods are used for obtaining the energy release rates G_{I}, G_{II}, and G_{III} (or the so-called crack intensity factor, such as K_{I} expressed via G_{I} for the tensile mode of fracture, when assuming a simple stress or strain state). The energy release rate characteristic is derived from Linear Elastic Fracture Mechanics (LEFM); nonlinear effects in the vicinity of the crack are taken into account by the J-integral theory, which is used for assessment of a similar critical characteristic (J_{IC}) that is reduced to G_{IC} (the fracture toughness) for the linear case. The review in paper [Chaturvedi, 1985] concludes that the damage zone near a crack tip is subject to a number of fracture modes and, therefore, conventional approaches, dealing with a pre-selected mode of fracture, are unlikely to be successful for obtaining a comprehensive fracture criterion. It is suggested that the damage zone size and dominant damage mechanisms should be taken into account when constructing the fracture criteria.

A paper by [Kusaka, 1997] considers resistance curves (R-curves that take into account variability of fracture toughness with crack length) of carbon/epoxy composites. Fracture toughness G_{IC} for the first mode of fracture (tension normal to the crack surface) is studied. The Double Cantilever Beam (DCB) test was used under quasi-static loadings and the Wedge Insert Fracture (WIF) method (a modification of DCB) was used at higher loading rates. A sharp drop in the fracture toughness was observed at higher loading rates obtained with Split Hopkinson Pressure Bar (see later in this Section for details of the SHPB tests and the technique). Paper [Kusaka, 1997] relates the toughness decrease to the material rate sensitivity. However, the paper does not analyse if the choice of two different methods of testing, which provide two different strain rate ranges of loadings, influences the fracture toughness decrease.

The three-point bending test is used in paper [Salvi, 2003] for observation of the rate sensitivity of K_I. Pre-notched carbon fibre composite samples were loaded both statically and dynamically with a drop-weight machine. The material was of a unique unidirectional meso-structure. Crack displacement was measured with a grid gauge that had been marked directly onto a sample (crack propagation gauge). It is necessary to note that the through-the-thickness non-uniformity in crack propagation cannot be captured with such a gauge. A decrease of K_I with strain rate was observed in this study, which confirms the results obtained in the paper [Kusaka, 1997].

These studies show that crack propagation fracture, which is a dynamic process by definition, can also exhibit rate sensitivity. Therefore, it is also necessary to verify whether the mechanical characteristics such as elastic modulii, limit stresses, and strengths, which have always been treated as material constants, remain constant within a wide range of strain rates as well, or if they are actually rate sensitive. This is important because the analysis and prediction of material behaviour (and of material response as a whole) is very sensitive to the assumed mechanical characteristics.

Testing cellular materials is a challenge because of their characteristics, combining features of conventional, anisotropic, and porous materials. Tensile behaviour of an aluminium foam, using conventional tensile testing machines, at different relative densities and at a strain rate of approximately 10^{-4} sec^{-1} has been studied in paper [Despois, 2004]. Non-linear behaviour resembling elasto-plastic behaviour has been observed. It is interesting to note that no obvious linear elastic part of the curve was found, especially for foams with small-size cells. Compressive quasi-static behaviour of a similar foam material was studied in paper [Song, 2005a]. The compression behaviour of this cellular material is unconventional: the observed stresses and strains are 'apparent', i.e., the recorded stresses may not correspond to local instantaneous stresses at all points of sample. Because the material deformation is highly non-uniform, the material's apparent response reflects macro-behaviour of the sample and cannot indicate the micro-stresses and micro-strains being developed at the deformation. However, the general feature observed in all compression tests of foam materials is their 'porous' (the compaction regime at a relatively slowly changing load) and 'after compaction' distinctive characteristics. With static testing, this is the main feature of the compressive characterisation of foam materials.

Material properties under dynamic conditions are very important for analysing structure behaviour when subject to impact. The importance follows from the fact that the internal material response time might be longer than the load duration (i.e., the material state does not have enough time to adjust the transient external stresses with the internal microstresses of the material; in other words, the material relaxation time is larger than the load duration). For example, at impact a target material is loaded by shock waves that may have a rise time of just fractions of microseconds. It means that the strain rate could be as high as thousands of inverse seconds. State-of-the-art dynamic measurements deal with transient states of a sample at strain rates comparable to those being developed in shock waves. A range of special experimental devices has been developed in order to cope with these rates of load. The SHPB (Split Hopkinson Pressure Bar) is probably the most popular among these devices because the strain rates achieved in SHPBs are typically thousands of inverse seconds. Intermediate rate devices, such as hydraulically operated devices and drop-weight machines, have also been used for dynamic testing.

Due to the use of various methods employed in dynamic testing, the measurement method's influence on the testing results is a critical issue. Modern facilities attempt to describe the material response within a wide range of strain rates. Paper [Groves, 1993] describes a material testing facility and the use of the facility tools for the testing of a carbon-fibre composite. The facility contains: a drop weight tower (a compression testing machine) with a capability to test samples up to 100 sec^{-1}; a fixture for tensile testing in the same range of strain rates employing dog-bone shape samples; and a fixture for shear testing of bar-shaped samples using a testing rig which provides three-point bending. In the tests, the carbon-fibre composite exhibits a sharp increase in sensitivity to strain rate change from 10 to 50 sec^{-1} for tensile testing. The testing fixtures require laborious preparation and manufacturing of samples, with possible methodological sensitivity of the test results to the manufacturing processes. Variations in apparent rate sensitivity, which might be associated with testing by different facilities, gives reasons to conclude that methodological issues (facility dependence) are yet to be resolved.

An attempt to assess mechanical properties of a polymeric composite ($[\pm45]_{2S}$ sheet samples tested under tension in the in-plane direction) has been undertaken in paper [Papadakis, 2004a]. The samples were tested at three different low strain rates (10^{-3}, 10^{-2}, and 10^{-1} sec^{-1}) using an Instron testing machine The paper claims a slow rate dependence of the shear strength (less than 10% increase could be within a statistical dispersion) and a noticeable rate dependence of the shear modulus (20-30% decrease with every increment of strain rate). However, factors such as a possible accumulation of damage during the loading cycles, which can be a reason for the rate dependence, have not been analysed.

In paper [Jendli, 2004], another series of tensile tests for glass/polyester composite are reported. Composite samples were tested with a servo-hydraulic machine at strain rates from 10^{-4} to 10^{2} sec^{-1}. The study demonstrates no rate sensitivity for elastic modulii and a noticeable rate sensitivity for ultimate stress (more than 60%). The stress-strain curve has a piecewise linear character with slope changes at 30% and 70% of the ultimate stress. This change of regimes is explained by the damage factor, however, involvement of different constituents of the composite in irreversible deformation might be another reason for this change (see [Resnyansky, 1997a]).

Thus, the recent trend in material characterisation for dynamic response is to measure material properties at various load states (stress states) and at various load rates (strain rates). Yet another issue is how to take into account the history of loads and the material memory. This issue is still being discussed in the scientific community. State-of-the-art experimental techniques cannot yet deliver the necessary data that could be used to consider the influence of a material's loading history upon the response of such structurally complex materials as composites and cellular materials.

The material history influence is particularly difficult to control at high strain-rates. Recent efforts in this area include, for example, so-called interrupted tests. Interrupted tests are conducted with specially designed set-ups to load a sample up to a certain limit and to perform a repeated loading in order to study the response of the pre-loaded or pre-damaged material (see for example [Jendli, 2005]). In paper [Jendli, 2005], an experimental testing and multi-scale analysis of glass/polyester composite at a variety of strain rates with an interruption introducing damage, has been conducted. The study has revealed that the load rate does not affect the elastic modulii, whereas the damage onset and the damage kinetics are sensitive to the strain rate. Specifically, the rate dependent kinetic behaviour of material deformation with damage, which is typical for viscous materials, is highly relevant to the material response when loading a sample orthogonally to the fibre direction.

Testing under complex stress states is difficult and is a relatively new area in material characterization. Static testing machines are used with lateral confinement of a cell using loading cells for control of the lateral stresses. Bi-axial load testing of honeycomb samples at static and dynamic (low-velocity impact) conditions is reported in paper [Chung, 2002a]. In those tests, the lateral load was kept under control by load cells at a constant stress. The testing produced a limit stress envelope that is similar to the stress limit surfaces obtained for brittle and porous materials. Some rate sensitivity of the limit stress was observed. It might be suggested that the anisotropy of the material, which is induced during the loading, undermines the value of the envelope representation due to the history-dependent behaviour of the material.

In paper [Zhang, 1998], testing over the strain rate range from 10^{-3} sec^{-1} up to almost 100 sec^{-1} was conducted for several polymeric foams using an Instron testing machine and a pneumatic impact machine. In this study, the most extensive testing program was performed for polyurethane foam under simple and complex stress states. The program included uniaxial compression and tension plus shear testing and hydrostatic compression (the latter was carried out for samples submerged in a fluid under pressure). Temperature effects in the range from –20 up to 80° C (the uniaxial compression condition) were also studied. Noticeable rate and temperature sensitivities were observed, but the paper does not provide a methodological analysis of a strong increase of the rate sensitivity that was observed when the testing facility was changed from the Instron machine to the pneumatic facility.

Testing of samples under a complex stress state has been reported within a high strain-rate range. For example, the European Joint Research Centre possesses a number of devices including ones capable of testing at an intermediate range of strain rates (hydraulically driven devices with the loading rates from 10^{-1} up to 10^{2} sec^{-1}) and SHPBs (the loading rates over 10^{2} sec^{-1}) simultaneously loading a sample in two (see [Albertini, 1979]) and even in three (!) perpendicular directions (see [Albertini, 1991]).

3.2 The Split Hopkinson Bar compressive testing

At present the Split Hopkinson Bar (SHB) device is the most reliable facility for measuring material stress-strain response at high strain rates. The state of the art SHB theory and data interpretation can be found in paper [Gray III, 2000a]. Review [Chiem, 1995] lists papers on SHB testing of composites. The review establishes the requirement for a sufficiently large sample to be used in the SHB tests in order to accommodate a representative volume of material. The review also establishes the importance of the interlaminar damage mechanisms during SHB testing of composite samples, which contribute to the stress-strain behaviour of samples having rather limited dimensions.

Traditionally, the Split Hopkinson Pressure Bar (SHPB) consists of two main bars (incident and transmitter bars) that allow a deformation pulse to be formed, for it to propagate along the bar and to be recorded during its travel. The pulse is generated by impact of a striker bar against the incident bar. A sample is sandwiched between the two main bars so that the pulse propagating from the incident bar into the transmitter bar is attenuated due to the presence of the sample. The sample's stress response along with the strain rate can be derived from the analysis of the stress pulses (incident, reflected, and transmitted pulses) recorded at the midpoints of the incident and transmitter bars.

Anisotropy of composite materials and the non-uniform behaviour of samples under off-axis loading complicate the SHPB testing of composites. Nevertheless, there have been many attempts to test composite materials with SHPBs. The use of SHPB techniques for testing cellular materials is reviewed in subsection 3.4.

A simplified direct impact design of the SHPB (which was suggested in paper [Field, 2004]) has been used for testing metal/matrix composites in paper [Cimpoeru, 1990]. This SHPB operates with the impactor hitting a sample directly, omitting the incident bar. As a result, the input stress pulse cannot be controlled and the velocity of the impactor bar is the only source of information about the input stress pulse. Possible stress non-equilibrium caused by acceleration of the input bar with a propellant as a source of oscillations of the input pulse for the direct impact SHPBs has been studied in paper [Resnyansky, 2000]. With the simplified SHPB design it is impossible to record directly the strain rate (the direct impact SHPB can record just one transmitted pulse. Incident and reflected pulses recorded at the input bar of the classical SHPB, which allow evaluating the strain rate, are absent in this system due to absence of the input bar). The only way to control the strain rate in the simplified SHPBs is through indirect evaluation of strain rate via the impactor velocity. Possibly this is a reason for the fairly high strain rates reported with such SHPBs in paper [Cimpoeru, 1990; Field, 2004]. This SHPB device has also been used in paper [Shah Khan, 1998] for testing glass reinforced plastics. The lack of control of the strain rate from the transmitted pulse may be a reason for an apparent absence of rate sensitivity, which was claimed in this study within the strain rate range from 1000 sec^{-1} up to 4000 sec^{-1} (these composites may actually exhibit a fair rate sensitivity in dynamic tests).

Composite specimens frequently fail during SHPB testing. Therefore, many studies analyse fracture mechanisms by post-mortem inspection. For example, paper [Sierakowski, 1971] reports on the mechanical properties of steel/epoxy unidirectional composites as a function of the fibre concentration, filament thickness, and the composite structure. The yield stress limits were found using a static testing machine and SHPB. In this study, fracture modes were associated with delamination and fibre buckling during static testing and were accompanied by fibre breakage in the dynamic regime. The loading was performed along the fibre direction. An optimum in the fibre concentration for achieving the highest strength was noted. Samples with smaller diameter filaments resulted in higher compressive strength of the composite.

A study of carbon/epoxy fabrics (plain and satin weave) is reported in paper [Hosur, 2003a] using a static testing machine and a SHPB in order to observe possible rate sensitivity; samples were loaded in two directions (in-plane and through-the-thickness). Failure strain seems to be critical for this study. For the in-plane loading of both weaves the failure strain is quite low and peak stresses followed by softening are clearly visible. For the case of the through-the-thickness loading direction the unloading occurs immediately after the peak stress has been reached. The latter occurs due to a short loading pulse, which resulted from a short length of the SHPB's striker bar (just 22cm). The maximum possible stress is obviously not achieved, which is indirectly confirmed by the micrographical studies in this work reporting that there is no essential damage for through-the-thickness loading. It is highly likely that, due to this underloading in dynamic tests, the static peak stress recorded is higher than the peak stress recorded at high-strain rates in these tests [Hosur, 2003a]. At the same time, the in-plane loading results are rather conventional, demonstrating the limit stress rise with increase of strain rate. Clearly, methodological issues are very important for interpretation of the SHPB testing results in this type of experiment.

In paper [Ochola, 2004], Carbon-Fibre Reinforced Plastic (CFRP) and Glass-Fibre Reinforced Plastic (GFRP) samples were tested in the in-plane direction with a SHPB device and a hydraulic testing machine. Some rate sensitivity for the GFRP samples (nearly 10%) was noted, but no sensitivity was observed for the CFRP samples. Similar conclusions about the higher rate sensitivity of GFRP in comparison with CFRP have been made in paper [Wang, 2005] when testing both with an Instron High Rate testing machine (strain rates of the order of 10 sec^{-1}) and with a static Instron testing machine. It should, however, be noted that the SHPB tests conducted in the paper [Ochola, 2004] demonstrated a noticeable plastic regime for GFRP and a linear elastic regime under static conditions. CFRP displayed linear responses up to failure under both static and dynamic conditions. Therefore, fracture effects seem to be critical in this study.

Rate sensitivity of an S2-glass-reinforced polyester composite has been studied in paper [Khan, 2002]. This study analysed both failure modes and failure stresses/strains under quasi-static and dynamic conditions. For dynamic tests both Split-bar and Direct-impact SHPB designs were used. In the case of Direct-impact testing a strain gauge was mounted directly on a sample. The stress-strain response was found to exhibit a higher non-linearity in the dynamic tests when compared with the quasi-static test results. In all the tests the strength was observed to be essentially higher with loading in the through-thickness directions. The failure modes and failure limits were found to be highly rate sensitive for the GFRPs in both the in-plane and through-thickness directions of the composite material. When comparing results of the Direct-Impact and Split-bar tests, the stress-strain response was observed to be comparable; however, a noticeable non-linearity was higher for the Split-bar design. It seems that the Split-bar analysis involves wave non-equilibrium that passes on to the input- and output-bar gauges, whereas the stress response is analysed directly in the case of the Direct-impact tests.

The SHPB compressive testing of graphite/epoxy quasi-isotropic laminate composites is reported in paper [Dee, 1997]. The range of loads is from 300 up to 1200 sec^{-1}. Two directions of loading were employed: the in-plane direction and the through-thickness direction. The yield limit stress and strain, the ultimate strength, the ultimate strain, and the Young's modulus were obtained from the tests. The data show the yield limit strain of 0.5-0.7% along with an ultimate strain of 1-1.5%. The data on the elastic modulus are questionable and should be further analysed because the samples did not achieve equilibrium within the given range of strains; a substantial discussion and the sample equilibrating reasons why the elastic modulii are not achievable in SHPB tests can be found in [Gray III, 2000a]. As a result, the authors of the paper [Dee, 1997] observed a very big scatter in the elastic modulus data.

Assessment of fracture properties with SHPBs is an important application of the SHB testing technique which is being extensively developed. For example, paper [Nwosu, 1997] studies fracture (perforation) of composite samples using the SHPB set-up. A head with a punch mounted at the end of the SHPB's incident bar is used as a modification of SHPB for fracture studies. Thin cylindrical plates (1 to 4 mm) of a graphite/epoxy composite are used as specimens. Incident, reflected and transmitted pulses are recorded for a conventional assessment of the processes related to the material properties of the specimens. Absorbed energy is evaluated as a quadratic dependence of the difference between the incident and transmitted pulses. This evaluation is derived from an analogy in the assessment of the absorbed energy from the difference between the impact and residual energies at ballistic impact; however, the force-displacement response is not assessed. A similar set-up has been used in paper [Bedouet, 2002] for experimental assessment of damage evolution in metal-matrix composites (a quasi-isotropic lay-up). When the high strain-rate tests were compared with static tests (that were also conducted in this study), a higher localisation of damage at high-strain rates was noted. An early attempt at monitoring the failure response of glass/thermoplastic resin composite was conducted in paper [Latailllade, 1988]. A device suggested in this study approximated a SHPB of the direct impact design: an instrumented 60cm-bar (two gauges were mounted on a bar of diameter 10, 20, or 25 mm; the bar was typically hemi-spherically tupped) was in contact with a simply supported composite target (the target dimension was from 100 to 200 mm). This bar was impacted by a dropped bar (the bar materials were steel, aluminium or PMMA and the impact-bar lengths varied from 10 to 100 cm) from different height, which allowed the authors to vary the impact energy. Obviously, two gauges were not necessary in order to record the input and reflected pulses; however, keeping in mind the possibility of the impactor bouncing, perhaps, this two-gauge design is a necessity. It should be noted that interpretation of the records is likely to be difficult (for examples, an influence of the speciment shape – circular or square – on the damage mode was noted in this paper) and no records were presented in this publication [Latailllade, 1988].

Apart from fracture effects, the issue of the influence of different experimental facilities (in this case, static machine and SHPB), when comparing static and dynamic data, should also be considered. For instance, when studying a glass/epoxy composite loaded in the in-plane and through-the-thickness directions, the data obtained in paper [Song, 2003] with a static testing machine and a SHPB are particularly illustrative. Whereas the in-plane testing demonstrates a monotonic dependence of the strength versus the strain rate, when comparing the quasi-static and dynamic results, the through-the-thickness test results are grouped into two very distinctive sets. A fair separation between those data sets thus demonstrates a possible methodological divergence that is associated not with material properties but, rather, with the experimental devices from which the data were obtained.

Testing facilities used in paper [Hosur, 2003a] have also been used in a companion paper [Hosur, 2004a] for testing graphite/ epoxy composites with satin plain weave. In the paper [Hosur, 2004a], however, only samples in two in-plane directions were tested. Temperature was also a parameter of this experimental study and samples were tested at normal and elevated temperatures. In the majority of the tests reported failure strain was less than achieved strain, so the test results were conventional. Both the satin and the plain weaves demonstrated similar rate sensitivity (3-4 times in magnitude with rate variation from the static range up to 1000 sec^{-1}), with higher strength for the satin weave.

In paper [Song, 2004], testing of glass/urethane samples (6.25 mm dimension cubes) with a standard SHPB was carried out at low temperature conditions (from approximately − 200° C to +25° C). The loading was conducted in all three principal material directions aligned with the material symmetry axes. The samples were shattered during the tests. The sample strength, elastic modulus, and fracture energy were reported versus temperature at the strain rate of approximately 2000 sec^{-1} (fracture energies were probably calculated from the stress-strain response prior to fracture). It should be noted that the elastic modulus reported in the paper [Song, 2004] should be questioned because the elastic region of the stress-strain response was recorded by SHPBs prior to the stress state having achieved equilibrium in the sample. The method of cooling composite samples used in this study should be critically analysed as well. The sample was placed in a liquid hydrogen bath (–196° C) and the testing was conducted when a thermocouple gauge read out the temperature value to be used for testing. This reading was made during the temperature rise so that the test temperature was higher than the liquid hydrogen temperature. During this overcooling, the constituents may have undergone some chemical and mechanical changes that do not occur when material subject to high strain-rate loads is not overcooled. The temperature heterogeneity in the through-thickness direction of the sample, when increasing the temperature after the liquid hydrogen bath, might also be of some concern. Nevertheless, the data reported in the paper [Song, 2004] are valuable and they demonstrate significant temperature dependence of strengths in all directions of the material symmetry (nearly 5-6 times in magnitude). Another issue related to the validity of data is associated with a possible temperature gradient within the sample when the sample is in contact with the device's loading bars. The temperature distribution within the sample is unknown, since the thermocouple gauge can guarantee the pre-selected temperature only at the gauge's location. Special attention to the importance of the temperature gradient with time on the composite specimen quality prepared for SHPB testing has been noted in review [Gray III, 2000b].

In paper [Haque, 2003], SHPBs are used to study the effects of environmental conditions (moisture from dry to saturated conditions in matrix) and elevated temperatures (from ambient to 200° C) for glass/vinyl-ester woven composite loaded in both through-the-thickness and in-plane directions. As the paper shows, a slight decrease in strength correlates with an increase in moisture (about 10%) and a significant strength increase correlates well with the strain rate rise from 500 to 1500 sec^{-1}. The methodological issues already mentioned above are relevant for such a study, including validity of the conducted assessment of elastic modulii and the possible influence of temperature gradient in the input and output bars. The latter is caused by the climatic chamber arrangement where the bars' ends are placed into the chamber (a furnace) together with the sample, which introduces a temperature gradient in the two bars, possibly affecting the data taken from the SHPB analysis. This temperature effect was considered in paper [Bacon, 1993]; in this paper a correction method was suggested in order to take into accout the impedance variation in the input and output bars, which is associated with the heating of a sample in a chamber embracing the sample and the ends of SHPB bars. These issues, however, have not been considered in the paper [Haque, 2003].

3.3 The Split Hopkinson Bar tensile, shear, and off-axis testing

Material properties of structural materials vary significantly depending on the type and direction of loading. This may require highly specialised test facilities depending on the conditions and rate of loading and characterisation of structural materials under tension and compression occurs within two rather independent areas of study. In particular, Split Hopkinson Tension Bar (SHTB) facilities are typically different in design to SHPB facilities.

Paper [Harding, 1983] describes one of the first SHTB devices transmitting a tensile pulse through a fork-type inertia incident bar. Dog-bone shape specimens made of carbon/epoxy (CFRP) (0° orientation) and glass/epoxy (GFRP) (0° and 45° orientations) have been tested in this study. A three-gauge configuration on the input and output bars is used with one auxiliary gauge mounted on the sample. An increase in the elastic modulus for CFRP is claimed, which is questionable due to the non-equilibrium state in the sample during the loading process. The high inertia of the input bar in this SHTB design introduced serious methodological problems that have lead to more advanced but simpler designs. Strain rate sensitivity was not observed for CFRP up to failure. For GFRP, however, significant strain rate sensitivity was reported, which is in agreement with the compressive

SHPB test data discussed in the previous subsection (see [Ochola, 2004; Wang, 2005]). It should be noted that the absence of strain rate sensitivity for the failure stress limit does not imply strain rate insensitivity for the material's stress limit. Rather, it is necessary to carefully analyse the failure effects in such tests, which may prematurely result in a sample's fracture (for example, possible influence of the sample scaling).

Similar tests for carbon/epoxy, Kevlar/epoxy, and glass/epoxy woven composites have been conducted in paper [Welsh, 1985]. The samples were 3 mm in thickness with the cross-section of the dog-bone sample of 1.5 mm. Width of the samples was 9.5 mm and length of the working zone was 6 mm. The tests were conducted at strain rates of approximately 0.0001, 10, and 1000 sec^{-1}. For CFRP, cracking was observed immediately after the linear elastic part of the stress response. However, a plastic deformation before fracture was recorded at higher strain rates and some strain rate sensitivity was reported. Behaviour for KFRP was similar with slightly higher failure strain. A different behaviour was observed for GFRP with an increase in both the failure strain and the maximum stress versus strain rate. The results [Welsh, 1985] show that the maximum stress increase is quite significant in the strain rate range from 10^{-4} up to 20 sec^{-1} and that it is not very significant from 20 up to 1000 sec^{-1}. The fracture onset appeared to be rate independent for carbon and Kevlar composites and rate dependent for the glass composite.

SHTB tests for hybrid carbon/epoxy – glass/epoxy composites were reported in [Harding, 1972]. Static testing of the samples was also conducted. The study concluded that the failure strength of hybrid composites was higher than that predicted by the mixture rule. The report's judgement about the rate sensitivity of the elastic modulus may be questionable because of the methodological difficulty of obtaining elastic characteristics with SHB.

Paper [Shim, 2001] studies the high strain-rate tensile behaviour of aramid (Twaron) samples subject to SHB tensile tests. The tests were conducted with a 'conventional' SHTB device that is not described; the strain rate varied from approximately 200 up to 500 sec^{-1}. The dynamic results are compared with quasi-static results (up to 1 sec^{-1}) obtained with a Shimadzu testing machine and significantly higher rate sensitivity was observed. It should be noted that the rate sensitive stress-strain curves are grouped into two clusters – quasi-static and dynamic (the curves obtained with static machine and SHTB, respectively). The data within these clusters are closely comparable. The authors extrapolated the data into the intermediate range of strain rates (from 1 up to 200 sec^{-1}) in order to construct a constitutive model. Increase of the elastic modulus and decrease of failure strain were claimed. The SHTB test facility used in this work may contains several structural elements (e.g., sample clamping fixture) which modify the transfer of the tensile pulse to the sample and distort the pulse passage from input bar to output bar. It would have been useful to test conventional materials using this fixture, but such tests have not been reported. Lack of such methodological studies leaves unclear the time of equilibrating of the stress in the sample material. As a result, it is very hard to judge if the failure strain reported corresponds to the start of release from the incident pulse (due to a short duration of the pulse) or if this strain actually corresponds to material failure. The parameters of the device are not reported; however, for conventional SHB devices the elastic modulus is usually not deducible from the strain-strain response due to lack of the time to achieve equilibrium during the elastic stage of deformation. Quasi-static stress-strain response is rather non-linear and it is not clear if the increase of slope of the stress-strain curve reported is associated with the change in the elastic modulus or with the rheology of the material (including micro-damage). Moreover, although the authors stress the importance of rheology when interpreting the extrapolation from the static data to dynamic data, they leave the rheology out when interpreting data within each group of the tests.

The SHTB configuration first suggested in paper [Albertini, 1974] contains just two bars; a part of the input bar is clamped and preloaded (tensed) and a clamp can quickly release this part of the bar thus transmitting a tensile pulse into the assembly containing the unloaded part of the input bar, the sample, and the output bar. Special care should be taken in the designing of the release clamp because the quality of the clamp and release mechanism is directly linked with the quality of the tensile pulse. Nevertheless, this is the only SHTB design which does not require intermediate flanges, extension parts, or structural elements for transmitting the tensile pulse. Therefore, with a quality clamp, this device, realising the pre-tension-release principle, might produce the best possible tensile pulse with a shortest rise time.

The most obvious idea is generation of tensile pulse by an impactor through a flange at the remoted end of the input bar. One of the first realisations of this design has been suggested in paper [Kawata, 1979]; this design had the simplification of direct impact SHB devices because the tensile pulse was generated by an impactor attached to a rotating disk through a flange attached directly to a sample. Testing with a tensile SHTB, in which a tensile pulse is generated by impact of the cylindrical tube striker bar against a flange of the input bar, is described in paper [Gómez-del Río, 2005a]. This design follows the classical SHPB design most closely, and, therefore, interpretation of the test results is quite similar to the classical SHPB analysis. However, the pulse quality due to the transmission of the tensile pulse via the flange to the incident bar suffers because of the design (apparently, this transmission mechanism smears out the pulse front on a width comparable with the bar diameter). Samples of CFRPs with unidirectional structure in the fibre direction and lateral direction and samples with a quasi-isotropic lay-up (in-plane direction) have been tested at normal and low temperature (–60° C). A specially designed climatic chamber has been attached and a study has been conducted to demonstrate that a signal change due to the temperature variation in the low-temperature conditions at the ends of the input and output bars adjacent to the sample is just comparable with the signal noise and, therefore, can be neglected. The strain rate used in the tests was around 1000 sec^{-1}. The tests showed a significant strength rise (more than twice in magnitude) at the low temperature only when unidirectional samples in the lateral direction were tested.

Traditional SHB tests record the stress-strain response at a variety of strain rates. The shear mode of deformation was realised under torsion in paper [Chiem, 1987], which described SHPB testing of woven carbon/epoxy composites. A cubic-shaped sample was placed between the ends of the input and output bars, which have been modified/grooved in such a way that they can accommodate the ends of the sample. A torsional load is hydraulically applied and quickly released, transmitting the torsional wave through a sandwich assembly containing the input bar, sample, and the output bar. This facility exploits the same design as that described in the paper [Albertini, 1974], replacing the pre-tension-release principle by the pre-torsion-release principle. The shear stress-strain response observed was typically elastic, followed by fracture with critical failure strain of nearly 20%. Static tests provide nearly 70% of the critical failure strain but much lower maximum shear stress than in dynamic tests.

Paper [Kumar, 1988] describes high strain-rate testing of GFRP and CFRP with torsional SHB. A torsional load is applied at a part of input bar and quickly released, generating a torsion pulse. This facility employs the pre-torsion-release principle (see review of the paper [Chiem, 1987] above). The tests show no rate sensitivity of the materials for the shear limit stress; strain before failure in the tests approached 10%. For comparison, similar tests conducted for the epoxy material have demonstrated significant rate sensitivity.

For a SHPB study of composites subjected to the shear mode of load, specially designed specimens are necessary. Paper [Harding, 1989] describes compression, tension, and interlaminar shear tests for carbon/epoxy composites. In those tests, a conventional SHPB for compression and a SHTB for tension and shear tests (the SHTB device described in the above-mentioned paper [Harding, 1983] was used) have been employed. The shear sample was prefabricated in a γ-shape with a central PTFE spacer in the upper part of the sample (the middle sample section was clamped at one end of the tension assembly and the upper section of the sample, separated by the spacer, at another). Tension of the sample prefabricated in such a way results in shear deformation in the sample. The tests show negligible rate sensitivity to failure and a rate sensitivity of maximum stress for all modes of testing for carbon/epoxy composites.

Report [Li, 1990] uses the same set-up for interlaminar shear testing between two carbon plies, two glass plies, and one carbon and one glass plies. The SHTB uses a conventional design where a tube impactor, accelerated by a gas gun, hits the flange of the input bar in order to produce a tensile pulse. The results show highest interlaminar strength in both static and dynamic tests for carbon-carbon specimens and the interlaminar shear stress is found to be strain rate dependent for all tested combinations.

The punch-die configuration in SHPB tests is very popular because it easily allows one to use traditional SHPB devices along with a simple fixture to test samples in the high strain-rate regime in a shear mode of loading. However, it is not easy to interpret the data obtained in such tests. For example, punch-die (shear cut-out) tests were conducted in report [Harding, 1972] for glass-reinforced plastics (GFRP). An Instron testing machine and hydraulic testing machine were used along with SHPB in this study in order to cover a wide range of loading rates. Testing of 2 mm samples showed a wide scatter of data, possibly due to large inhomogeneities with the 2-mm scale, when comparing dimensions of the material’s structural elements with the sample’s thickness. This choice of the sample's dimensions results in a small number of representative elements in the volume. However, an increase of the peak load with the loading rate is clearly seen from the tests. In order to reduce the scatter, 3.2 mm-thickness samples were tested. The load-displacement curves demonstrated no knee under static loads with a smaller peak load (the 'knee' load corresponds to the onset of shear cut-out). When increasing the loading rate, an increase in the knee and the peak loads was observed. Failure was observed in the form of fibre breakage and delamination/debonding. Another GFRP which was tested had a very regular structure. This material showed the same results with the 5%-scatter and only a fibre breakage as the failure mechanism. Similar SHB tests conducted in paper [Harding, 1979] for woven-roving glass-reinforced composites showed presence of the 'knee' at high-strain rates and quite high rate sensitivity. Keeping in mind the rate sensitivity of the 'knee' effect, it appears that it is associated with the viscous nature of the composite matrix.

Paper [Nemes, 1998] describes quasi-static and SHPB tests of graphite/epoxy composites in a punch-die fixture within set-ups which are identical for static and dynamic cases. The paper provides an analysis of the influence of the stacking sequence, mismatch angle, sublaminate thickness, and overall thickness on the results. It is argued that the stress response has a 'knee' load, peak load, and a softening zone exhibiting a decrease in the load resistance. The results demonstrate that the knee load and the peak load for static cases differ significantly from these loads for dynamic cases. In the SHPB tests, the stress-strain response and the corresponding absorption energy are not significantly affected by the laminate parameters. It is concluded that, from the modelling point of view, quasi-isotropic laminates can be considered to be transversely isotropic solids. It should be noted however, that the onset of the failure could not be predicted with such approximation, because the fracture behaviour is dependent on the laminate and interlaminate adhesive parameters. Therefore, such modelling needs to be specific for each individual case. As comparison of the results of static and dynamic tests has shown, the knee load is higher and the peak load is lower for the dynamic tests, which resulted in a decrease of the absorbed energy at high strain rates observed in the study [Nemes, 1998]. The knee load provides a shear stress (yield) from the circumferential area of the punch; this load is consistent with available shear stress data. This paper thus shows that measurement of absorbed energy under static tests cannot be used for assessments of the energy under dynamic penetration.

Several other quite complex devices, which can generate tensile pulses, are being developed and employed for tensile testing at high strain rates. For example, the flying wedge technique has recently been presented (see [Cole, 2003; Mirza, 2003; Sturges, 2001]). This technique, however, requires further development of its recording methodology. Currently, the sample deformation is monitored with optical methods or with a strain gauge. These methods have known deficiencies because this facility allows one to measure strain only; a relevant recording technique has yet to be developed for this method. In many cases, plastic behaviour followed by fracture is observed and detailed studies are undertaken to connect the elastic and fracture behaviour of composites at high strain rates. Paper [Xia, 1993] describes SHTB tests of a glass-epoxy composite. The SHTB is based on the break device when a pendulum impactor hits a block separating it from the input bar and generating a tensile pulse. The paper shows a rate sensitivity of the composite and claims a ductile-brittle transition since the material manifests plasticity at low strain rate and fails without a plastic deformation (elastically) at high strain rates.

Off-axis testing is not easy with the SHPB technique because unbalanced composite samples tend to be obliquely squashed by shear and provide unreliable data. Static tests on the stretching of a thin composite rod in the off-axis set-up, and tube tests of composite samples under internal pressure have been described in references [Jones, 1985] and [Uemura, 1981], respectively. Off-axis tension tests for a metal matrix composite under static conditions were also conducted in Purdue University, USA (see [Sun, 1990]). Stress-strain curves were built up for a wide range of fibre-load axis angles from 0 to 90 degrees. The test results show a larger hysteresis in the load-unload cycle for the case of stronger off-axis load. In the paper [Sun, 1990], this effect is associated with the fibre-matrix delamination.

The team from Purdue University conducts a variety of the off-axis tests on composites, including static and SHPB tests. For example, paper [Kim, 2002] experimentally studies the off-axis response of AS4/PEEK (a CFRP) unidirectional composite during the loading-unloading cycle at a variety of low strain rates. The corresponding relaxation of the stress-strain response to a master stress-strain curve, which is observed in the tests, is associated with the fibre direction realignment.

Publication [Tsai, 2004] reports on the quasi-static and SHPB off-axis compressive testing of glass/epoxy composite samples in the range of strain rates from 10^{-4} to 1000 sec^{-1} and within the range of load axis-fibre direction misalignment angles from 5 to 15°. The paper studies the failure mechanisms and concludes that the compressive strength decreases more significantly with larger strain rate. The more extensive involvement of shear stress is considered to be the main reason for this observed decrease in rate.

Paper [Silvestrov, 1997] observes elastic-brittle behaviour for SHPB testing of Kevlar-, Glass and carbon-epoxy composites. The failure mechanism and strength are found to be strongly dependent on the loading direction (0, 45, or 90 degrees to the fibre axis). An unusual reduction in strength at the 45° loading is observed, which is likely to be associated with the fibre/matrix debonding during the loading of the unbalanced samples.

In paper [Preissner, 1997], the SHPB off-axis testing of Kevlar/Epoxy composites is reported. The paper also mentions a comparative SHPB study between cylindrical and cubic shaped samples. The test results [Preissner, 1997] demonstrated no effect of the sample shape on the SHPB results. This study focuses on the unidirectional structure and laminated (cross-ply) samples with nearly orthotropic material structure. The SHPB tests have been conducted in the loading direction for 0, 15, 30, and 45 degrees from the orthotropy symmetry axis. The strain rates vary from the quasi-static and up to the dynamic range (SHPB tests with a strain-rate range from 400 up to 800 sec^{-1}). It should be noted, when dealing with the off-axis testing, that the possible non-uniformity of the sample shape during testing due to material anisotropy is not taken into account. The influence of the fracture mechanisms (debonding, delamination, and fibre breakage or buckling) on the ultimate strength is yet another interesting issue that needs to be explored.

Paper [Weeks, 1998] describes the off-axis behaviour of AS4/PEEK composite laminates. A servohydraulic testing machine was used for the range of strain rates from 10^{-5} up to 0.1 sec^{-1}. The samples were of 16x216 mm in dimension with angles of 15, 30, 45, and 90° of the fibre orientations to the load axis. Similar tests were performed for balanced $[\pm\theta]_{2S}$ samples with θ equal to 0, 15, 30, 45, and 60 degrees. The composite samples, which were aligned with the loading axis (the 0° samples), did not exhibit plasticity or strain rate sensitivity. Therefore, the strain rate sensitivity observed for the both types of the composites with non-zero θ is thought to be associated with the matrix strain rate sensitivity. Because of the shear distortion feature for the unidirectional composites' samples (unbalanced samples), only the balanced samples for 90, ±30, ±45, and ±60 orientations with the dimension of 8x8x8 mm were used for SHPB testing. The range of strain rates was changed from 100 to 1000 sec^{-1}. The SHPB tests also demonstrated strain rate sensitivity. A plasticity theory with a constitutive equation similar to the Johnson-Cook equation is developed in the paper and used for description of the test results.

An experimental study of the tensile strength of metal-matrix composite as a function of fibre orientation with respect to the load axis has been conducted in paper [Jackson, 1966]. The study constructs the strength-angle curves and concludes that: at small angles, fracture is due to fibre breakage; at intermediate angles, fracture occuring mainly due to fibre-matrix debonding as well as damage in the matrix; while at high angles, fracture occurs mainly in the matrix.

Paper [Staab, 1995] describes SHTB experiments for glass/epoxy balanced laminates using a SHTB with the pre-tension-release principle (see [Albertini, 1974]) outlined above. In the paper, a 3-gauge arrangement was used: two gauges are on the input bar and one gauge is on the output bar. Dog-bone shape samples were glued to a cylindrical holder. Alternatively, the samples were of a regular configuration mounted within a slotted cylindrical holder. The fibre orientations with respect to the loading axis were ±15, ±30, ±45, ±60, and ±75°. Static tests were also conducted. These tests are claimed to show high strain rate sensitivity for small angles and lower sensitivity for large angles. However, the data reported in this paper could be interpreted differently, since from an observation of the data, the most sensitive case seems to be the ±45° case, which is possibly associated with fibre-matrix debonding. Tests with the smaller angle samples exhibit elastic behaviour under static tests conditions and, therefore, it is hard to compare the static and dynamic test results.

3.4 The Split Hopkinson Bar testing of cellular materials

The most complex materials of interest for the rotorcraft industry are the honeycomb materials which are used as components of sandwich materials. These materials exhibit a wide range of features which can be typically observed in ductile, composite, and porous materials. When testing cellular materials, the drawbacks of the SHPB technique are the low impedance of the sample material and the material's highly nonlinear response. However, the number of attempts to test cellular materials with SHPB facilities is increasing.

The use of conventional testing machines to observe the rate sensitivity of cellular materials is also not unusual. A static testing of a honeycomb material in conditions of complex stress state has been conducted in paper [Chung, 2002a] (see subsection 3.1). The most interesting observation reported in this paper was that the deformation mechanism of the material cells makes this initially isotropic material acquire orthotropic anisotropy properties. The material behaviour might be even more complex if the stress state during deformation was three-dimensional. Even under quasi-static testing, honeycomb materials may exhibit quite high rate sensitivity. Data cited in the paper [Chung, 2002a] demonstrate an increase in the tensile stress limit by approximately 50% with the strain rate changing from 10^{-5} to 1 sec^{-1}. Another complication is that "soft" materials, including cellular materials, might be sensitive to the sample size, when testing with a SHPB device (see review [Gray III, 2000b]).

Paper [Mohr, 2004] provides a summary of uniaxial static compression tests on an aluminium honeycomb material which is anisotropic due to the non-symmetrical cell configuration. The tests show that the material response for different loading directions is basically of the same pattern (elastic response, compaction plateau, and densification) but the material responses vary since the plateau stress level depends on the loading direction.

Static testing of polyurethane foam conducted in paper [Shim, 2000] reported almost perfect elasto-plastic behaviour of this material under compression, before the compaction stage. Under shear testing, the material exhibits a nearly linear behaviour (up to the collapse stage when the stress response is approaching a plateau). Linear behaviour has also been observed in paper [Rakow, 2004] under shear testing of an aluminium foam material. Compression testing of this material with the same testing machine in the range from 10^{-5} sec^{-1} to 0.17 sec^{-1} demonstrated a rate sensitivity (about 10% rise in magnitude for the plateau stress). Nonlinear behaviour under compression has also been noted in these tests (see [Rakow, 2004]).

In paper [Baker, 1998], two different honeycomb materials have been tested quasi-statically: an aluminium honeycomb material with a cell size of 1 mm and with a thin cell wall, and a stainless steel honeycomb material with a cell size of 2 mm and with a thicker cell wall. A special constraint rig had to be used in order to minimize the specimen size effects (the rig design and conditions of constraint will be discussed in subsection 5.4). Load cell and position transducers were used in order to record the load-displacement response. As reported in the paper [Baker, 1998], an initial peak is noticeable before the start of a compaction plateau for both materials, with an extended non-linear response zone before compaction for the stainless steel honeycomb material. The character of the material collapse, which occurs at once for the whole volume of the specimen, explains this delayed compaction for the stainless steel honeycomb material. The aluminium honeycomb material collapsed gradually with a collapse wave propagating gradually from the indentor side.

In simple studies, the analysis might be limited to an integral response of a structure when loaded by the stress pulse transmitted through the incident bar (similarly to the direct impact SHPBs described in subsection 3.2). For example, in paper [Ruiz, 1994] the aim was an assessment of bird impact against an aircraft structure. Honeycomb and corrugated with a sine-wave shape core Titanium structures were tested with a direct impact SHPB. The rate sensitivity of the corrugated core structures was observed in this study.

Tests have been conducted in paper [Deshpande, 2000] with aluminium foams having typical cell sizes of 1 and 1.2 mm. An SHPB device, equipped with steel 12.7mm-diameter bars, was used for testing samples of 10 mm in diameter and thickness; the pulse length generated by the striker bar of this SHPB was 165 μsec. A direct impact design SHPB (see [Field, 2004]) was used for testing these foam materials. This study leaves many issues unresolved. For example, the authors claim that the dynamic effect in the pre-compaction stage can be ignored. However, the data obtained in this study demonstrate an oscillating stress response since the material samples are obviously in the state where equilibrium is not achieved. In addition, material specimens have only a few cells in the through-the-thickness direction, which does not allow the sample volume to be representative. Moreover, a very high impedance mismatch introduces additional electronic noise which is, perhaps, the major contributor to the gauge signal. The data contradict each other showing, in some instances, non-monotonic dependence of the material resistance (the compaction stress) on the strain rate. Thus, no clear judgement about rate sensitivity of the material is possible based on this work.

When analysing direct impact SHPBs in papers [Resnyansky, 2000; Resnyansky, 2002d], another possible source of spurious oscillations has been identified in the stress non-equilibrium in the striker bar, which is developed when the bar is loaded by propelling devices. There exist well-known methods of suppressing the pulse oscillations such as an intermediate bar or wave shapers placed between the striker bar and the incident bar (see [Chen, 2002; Song, 2003; Song, 2005b]). Wave shaping is recognised as one of the best methods of making the strain rate more uniform during the sample loading (see, e.g., [Chen, 2003]). However, the wave shaping reduces the achievable maximum strain rate.

When testing with SHPBs at high strain-rates, honeycomb and foam materials attenuate stress pulses dramatically so the signal reaching the SHPB’s gauges is very weak. This means that special modifications are required in order to successfully test cellular materials. For example, paper [Zhao, 1998] describes the SHPB testing of an aluminium honeycomb. This low-density structural material transmits a very weak response into the output bar if the output bar is made from steel. Therefore, modifications to the traditional SHPB facility are necessary. In this study, viscoelastic Nylon output and input bars of 3 m in length and 4 cm in diameter were employed. This allowed the researchers to decrease the bar-sample misimpedance and to increase the response by approximately 200 times for the SHPB bars when comparing with output for a SHPB with steel bars. SHPB analysis is extended to an inelastic calculation technique in order to eliminate the wave dispersion in the viscoelastic bars. The velocity of the impactor should be relatively low (2 m/s) in order to produce a readable record from the gauges. Samples of dimensions of 36 x 36 x 36 mm are used in the testing [Zhao, 1998]. One wave circulation is sufficient for the 5-mm displacement of a sample's side. Accordingly, a special recalculation technique is used in order to interpret a multiple wave circulation through the bar-sample-bar sandwich. The results show that only out-of plane crushing behaviour is rate sensitive (up to 40% increase in magnitude).

An SHPB study of lightweight polyurethane foams has been conducted in paper [Chen, 2002]. In order to increase the input signal for the gauges mounted to the main bars, the SHPB device used in this study was equipped with aluminium input and output bars which were instrumented with quartz gauges close to the ends of the bars that are in contact with a sample. The paper reports a strain rate up to 5000 sec^{-1}, which is surprisingly high, keeping in mind all the factors involved in traditional SHPB analysis. Restrictions of the classical SHPB analysis include a very moderate velocity of impact of the striker bar (this restriction should be satisfied in order to keep the bar's material in the elastic condition). In addition, a wave shaper between the impactor and input bar was used in the paper [Chen, 2002] in order to achieve force equilibrium faster, which inevitably reduced the strain rate. In order to ensure stress equilibrium in the sample during loading by the stress pulse, relatively thin samples have been selected (from 1.7 for the lowest density foam up to 3 mm in thickness) with the sample lateral dimension comparable with the diameter of the bars (19 mm). It should be noticed that for the lowest density foam just 5 to 6 cells fit into the sample thickness (the cell size is 0.3 mm), this thickness might not be large enough for the volume of the material to be representative. Thus, the size of the microstructural elements is of the same order as the thickness of sample, and, therefore, microstructural factors may prevail during the material compression. Nevertheless, significant strain rate sensitivity (at least two times increase in the stress magnitude) for this foam material was reported in this study [Chen, 2002].

Another study with the same SHPB facility was conducted in paper [Song, 2005c] for polystyrene foam. The sample thickness was 3mm with the cell size of 0.6-0.9 mm. Quasi-static tests were conducted with a compressive testing machine as well. Rate sensitivities for the collapse stress (plateau compaction stress) and the elastic modulus have been reported in the paper [Song, 2005c]. However, in the majority of the tests, the collapse stress reported is determined as the maximum stress that was achieved on the stress rise stage. Thus, this stress is limited by the strain reached; therefore, it is likely that the stress may change if the deformation reached is larger. Therefore, it is not clear if the stress rise is actually extinguished at the reported strain limit, because the unloading, following the stress rise, has interrupted the sample deformation. The tests have demonstrated a clear rate sensitive dependence of the collapse stress (the plateau compaction stress) for the dynamic range of loads and rate insensitivity within the quasi-static range of loads. It is worthwhile to note a sudden change of the rate sensitivity when comparing static and dynamic test results. It is quite likely that the sudden change of the rate sensitivity follows the change of type of testing facility. In this case, it is necessary to address this methodological issue. The reported dynamic dependence of the elastic modulus on strain rate is highly questionable because of the non-equilibrium behaviour of the collapsing sample during the initial stage of loading with the SHPB tests. The two-branch behaviour of the material, which is likely to be attributed to the choice of the testing facility, is inherited by a model fitted to the test data. Similarly to the publication [Chen, 2002], the claims made in the paper [Song, 2005c] regarding the rate sensitivity of the elastic modulus (the apparent 'modulus' is notably higher at a higher strain rate) are not substantiated. It is likely that the elastic modulus rate sensitivity is high in soft materials as noted in the review [Gray III, 2000b], whereas the elastic modulus-strain rate dependence is unlikely to be obtained reliably with the testing. The nonlinear stress-strain response at the initial stage of deformation clearly indicates non-equilibrium behaviour of material in the sample. This non-linear response is aggravated by the highly non-linear behaviour of the material in general, because the sample has only 4-5 cells in the through-thickness direction.

The use of nylon bars seems to be suitable for SHPB testing of foams. In paper [Thomas, 2004], for instance, two polymeric foams, which have the same density but different structures (linear and cross-linked), have been tested. The foams were tested statically and dynamically with a SHPB equipped with nylon bars at room and elevated temperatures (up to 100° C). In these tests, the cross-linked structures demonstrated less sensitivity to temperature than the linear structure foams. No significant influence of the strain rate on strength was noted at high strain rates for both foams and an increase in the stress response was reported when comparing the SHPB data with the static data. Methodological issues relating to the testing with different facilities might be relevant in the present case; however, these issues are not discussed in the paper [Thomas, 2004]. Recovery tests were used in this study, which allowed the authors to relate the presence of the gas trapped within closed foam cells with the change in the strength (compaction stress) properties of the foams. Post-impact tests on determination of the residual strength revealed a nearly constant dependence of the strength on temperature for the cross-linked structure foam and a strength increase with temperature increase for the linear structure foam. These test results showed that the trapped gas is an important factor which needs to be considered in the strength evaluation. The importance of this factor has also been shown theoretically in a study of the shock response of aluminium foams (see [Resnyansky, 2004b]), using the modelling approach developed in the same paper.

Even when the impedance of SHPB bars material (nylon, aluminium) is adjusted to the impedance of sample's cellular material, the sample's dimensions should be small enough for the sample to achieve stress equilibrium. Otherwise, the compaction takes an extended time due to the low sound velocity in the porous materials. This compaction stage could keep the sample out of equilibrium during the whole period of the loading. It is possible that this circumstance was a reason for the conclusion in paper [Yu, 2003] that for samples of 10 and 20 mm in thickness, no rate sensitivity was noticed in tests on aluminium foam material (average cell size is 1.5 mm). A study conducted in paper [Papka, 1994], which will be reviewed in detail in Section 5, shows that highly porous aluminium foams with weak cell walls deform progressively. It means that the cell collapse deformation (densification) propagates from the point of load (the same behaviour of aluminium foams was observed in the above-mentioned study [Baker, 1998]). Therefore, the uniformity of deformation, which is a necessary condition of the SHPB analysis, is highly questionable up to the point of densification of the whole volume of sample. To reach a relatively high densification a deformation of the order of 40-50% is required according to the data [Yu, 2003]. Thus, the sample should be contracted by 5-10 mm which means that the time of the contraction is of the order of 100 μsec. The length of the pulse in conventional SHPBs is nearly 100 μsec as well, so, the material does not have enough time to equilibrate, in addition to the likely non-uniform deformation during the densification. This is probably one of the reasons (in addition to the different nature of material which is an aluminium foam in [Yu, 2003]) why these results contradict the results obtained in [Chen, 2002] for a polyurethane foam. Therefore, the issue of rate sensitivity of the aluminium foam material should be further addressed in order to eliminate the contradiction between the results.

A SHPB study of syntactic foams (glass micro-ball filled epoxy) in confined conditions has been conducted in paper [Song, 2005b]. Static tests for this material have been conducted as well. The results of this study have been compared with the results for this material in unconfined conditions. The comparison has shown that the yield tooth which is likely to be associated with the fracture of the micro-balls is less for the confined tests (it is, nevertheless, noticeable – this yield tooth feature of the high-strain rate behaviour of syntactic foams in SHPB tests can be simulated within a phenomenological viscoelastic constitutive model as it has been shown in paper [Merzhievsky, 1992a]). Stress pulses in the study [Song, 2005b] are nonuniform because of a flange trap placed on the input bar to protect samples from repeated loading by a bouncing striker bar. Rate sensitivity is about the same for unconfined and confined tests. The static tests, however, demonstrate similar yield limits for confined and unconfined tests, which diverge at higher strain rates. In interpreting these results, factors such as the difference in testing facilities under static and dynamic conditions should be kept in mind. Another factor that may affect the quality of the SHPB signals is the use of bars made of Maragin Steel, which has a very high impedance mismatch with the sample material. Rate sensitivity of the elastic modulus is unlikely to be proven because of the usual problems of measuring the elastic portion of stress-strain curves with SHPBs (the elastic strain limit of 3% for this material means that the 4 mm-thickness sample is being compressed elastically during the first 5-10 μsec of the sample's deformation. With the average sound speed lower than 1 km/s stress equilibrium cannot be achieved sooner than 20 μsec after the compression). Further development of this work, taking into account the environmental conditions (temperature), resulted in SHPB tests with samples placed in a thermal chamber (from –50 up to 70° C) (see [Song, 2005d]). The tests demonstrated a higher temperature dependence of the yield (compaction) stress at lower strain rates (nearly 500 sec^{-1}) than at strain rates in the higher range (more than 1000 sec^{-1}).

An interesting study of the influence of the trapped air on the rate sensitivity of an aluminium foam material has been made in paper [Dannemann, 2002]. In this study, static and dynamic (SHPB) tests of the foam material have been conducted in the atmospheric-pressure and evacuated-air conditions. The foam has cell size from 2 to 4 mm and the sample length in the SHPB tests was 25.4 mm (the sample's diameter was 23.6 mm). The air evaculation was achieved within a small chamber attached to the ends of the input and output bars, which are in contact with the sample. Unfortunately, the SHPB device was not described; therefore, how the methodological issues (among which there are, e.g., a choice of the bar material, achieving representation of the material with a relatively small number of cells along the sample's length, possible pre-deformation of sample due to evacuation of the air from the chamber containing the sample) have been resolved is not clear. Samples of two types of material were tested: i) material with a closed-cell configuration; and ii) material with cells that were interconnected for the passage of air. The closed-cell material within the strain-rate range from approximately 10^{-5} sec^{-1} up to 2000 sec^{-1} exhibited much higher rate sensitivity (up to 100% increase of the stress response) and a high deviation between the dynamic results for evacuated and atmospheric-pressure samples, when compared with the interconnected samples that demonstrated a much smaller scatter of the flow stresses (up to 20-30%). It means that the trapped air is critical for the stress response of the closed-cell materials and it is not so critical for the open foam systems.

Paper [Benitez, 1997] reports a three-point bending test when a source of load is the far end of the SHPB input bar. Notched honeycomb carbon/epoxy laminates are studied. At an impact velocity of 10-30 m/s by the SHPB striker bar, the crack length-time curve is calculated from high-speed Cordin camera records. The paper concludes that within such load regimes, the crack damage is not severe, with an average crack velocity of 200 m/s. However, interpretation of data is not straightforward when compared with uniform loading of simple-shape samples. Paper [Zhou, 2004] couples SHPB experiments on pre-notched metal-matrix composite samples with direct finite-element modelling and suggest a methodology for the derivation of the crack propagation data from the test results, at the same time verifying the FEM model. It should be noted that the suggested strategy has a weakness in that the same data are used for both the model design and the model verification.

3.5 Non-destructive evaluation and monitoring

Evaluation of material quality and properties involves measurement of mechanical characteristics before, during and after a loading event. Evaluation during the process of loading (in-situ evaluation) is the most complex. A range of methods can help record relatively uniform data or data in equilibrium directly by testing machines equipped with instrumentation, such as gauges, loading cells and optical or mechanical recorders of the machine crossheads. Destructive methods of evaluation usually assess the state of a sample after mechanical test or a loading event and they require cross sectioning followed by an optical (micrographic) inspection. Non-Destructive Evaluation (NDE) methods are very popular, because they do not require mechanical intrusion into the material's structure and allow an assessment of the sample's integrity and even the stress state inside a sample before, during and after a loading event.

Assessment of the consequences of a damaging threat can be performed in various ways. Visual inspection with the naked eye is the most popular in the case of visible damage. It allows an assessment of such surface characteristics as the area of the visible delamination that appears as a discolouring at the target surface, or as bulging. Visual inspection has been used, for example, for an assessment of the surface at the distal side of a target after impact in papers [Cristescu, 1975; Ross, 1973; Sierakowski, 1981] in order to investigate interlaminar failure modes. The 'whitening' area was evaluated and used as a criterion of impact response to a ballistic event in paper [Ayax, 1991] and to a hypervelocity event in paper [Silvestrov, 1995]. In papers [Sierakowski, 1971; Silvestrov, 1997], classification of failure modes of composite samples at deformation during SHPB testing was performed visually. A study [Goldsmith, 1995] on Kevlar fibre targets subject to impact is a typical case when visual inspection is useful. Visual inspection may even provide parameters which can be used for prediction of ballistic performance (see, e.g., [Cunniff, 1999]). Measurements of the crack length (see [Gupta, 2001]) or visual assessment of failure modes for composite targets (see, e.g., [Ambur, 2001; Finnegan, 1993; Wu, 1990]) are widely used in post-impact analysis. Visual assessment of target damage followed by characterisation of the failure modes of honeycomb sandwich panels has been carried out in paper [Ruiz, 1994]. Recovered samples and debris after impact are also used for post-impact visual examination (see, e.g., [Woodward, 1991a]).

Damage to a witness plate is another means of assessment of the primary target's impact response. Using the witness plate method, the extent of the spread of debris due to ballistic impact against a brittle target is evaluated in paper [Hazell, 1998]. In papers [Cimpoeru, 1996; Rupert, 1993], Depth Of Penetration (DOP) of an impact threat in a witness plate is used as a criterion of the target response to the ballistic impact. DOP evaluation may also involve a destructive method of inspection, such as cross sectioning. The cross sectioning of a target is usually used in order to understand failure mechanisms. The sample's cross-sections can be inspected visually, either with a naked eye (see, for example, the failure analysis in papers [Gellert, 2000; Woodward, 1998]) or with optical or Scanning Electronic Microscopy (SEM) (see, for example, analyses of the micrographs of cross-sections in papers [Baucom, 2004; Cantwell, 1990; Hammond, 2004; Harding, 1972; Lee, 1993; Li, 1990; Luo, 1999; Meyer, 1997; Nahme, 1994; Zhu, 1992a]). Cross sectioning along with ultrasonic inspection was used for observation of delamination and sublaminate formation of carbon/epoxy composites with different stacking sequences in paper [Dost, 1991]. Cross sectioning followed by optical inspection has been used in metallographic studies of conventional materials for decades. Recently, it has also been used in paper [Karamis, 2004] for studies of metal-matrix composites. In paper [Dubouloz-Monnet, 2005], SEM inspection and morphological studies of original samples have been conducted for an assessment of fibre distribution and integrity of a composite material during the process of manufacture. These evaluations were followed by measurement of viscoelastic properties of the material from the same supply.

An advancement of optically instrumented inspection is interferometry to measure deformation of a sample. A comprehensive review of these methods, including speckle and Moiré photography and interferometry, can be found in paper [Grédiac, 2004]. A review conducted in paper [Field, 2004] outlines how these methods are applied in studies of isotropic materials, including the method of dynamic thermography (this latter technique is presently of particular interest in energetic materials studies). These methods utilize information about a sample's surface. They can be used for measurements before and after testing (when samples are stress released) as well as for in-situ measurements. Recently, an advanced application of Moiré interferometry in dynamic conditions for high velocity impact against a composite target has been reported in paper [Bruck, 2002]. The authors of paper [Bull, 2004] argue that digital speckle photography allows an evaluation of in-situ displacements and strains at the sample's surface during compression-after-impact tests. It should be noted however, that these methods cannot give detailed information about the stress state inside a sample and about changes in the sample's internal material structure.

The NDE of a sample before impact allows an assessment of the extent of initial damage (e.g., pre-impact damage due to manufacturing) of the sample to be tested. It also helps understand if this damage influences the sample's impact resistance. If in-situ NDE can be carried out, then an evaluation and analysis of the mechanisms of damage during the impact event are possible. The most frequently published cases of using NDE are based on the evaluation of samples after a loading event. This evaluation helps researchers analyse the extent of after-impact damage.

Usually, the same set of NDE methods is used for an inspection of samples before and after a loading event. For in-situ optical inspection however, special techniques need to be developed and applied. In paper [Onck, 2004], for example, a sample of aluminium foam subject to simple stress has been placed under the head of a scanning electronic microscope for in-situ analysis of fracture during tensile testing. A similar technique has been used in paper [Jendli, 2004] for testing thin samples of a composite material under tension. When the size of the foam cell is large enough, conventional photography can be used. Photographic in-situ observation has been conducted, for instance, in paper [Song, 2005a] when testing aluminium foams with different densities under compression.

Similarly, direct high-speed photography of samples loaded by a compact impactor can also be considered a method of NDE during the impact event. Because high-speed photography is highly specialised and is usually applied in high-velocity impact events, this method is examined in detail in subsection 4.1 which focuses on a review of novel experimentation methods for impact.

NDE acoustic scanning, or C-scanning, is an informative test method because it helps obtain information about structural changes in a material sample (see, e.g., [Bull, 2004; Hosur, 2004b; Kim, 2004a]). Its major disadvantage is the low resolution of basic scanners so that the method only allows researchers to evaluate an integral (averaged) distribution of the delamination density through the sample thickness. An advancement of the basic C-scanning method outlined in report [Fink, 2001] allows this method to be used for nondestructive damage evaluation through the thickness of a sample. This advanced method employs 3 waveform gated regions of scanning through the sample thickness at the depth levels of approximately 10% below the impact surface, at the target's midplane, and at the level of approximately 80% below the surface. Generally, the C-scanning allows one to obtain the two-dimensional distribution of flaws through the thickness of a sample. With the gating capability [Fink, 2001], the C-scanning technique is able to analyse the internal structure. This method, therefore, allows the authors to differentiate the damage with respect to the depth of observation. A similar approach is used in paper [Zhang, 1999] where an advanced scanning system (ANDSCAN) based on the C-scan technique is exploited. In paper [Gao, 1997], the impact damage of carbon/resin composites subject to low velocity impact is evaluated with three ultrasound techniques: the C-scan technique; time-of-flight analysis (ultrasound time-gated scanning to measure amplitude of the signal); and B-scan imaging (through-the-thickness determination of the defect distribution within a sample). These techniques enable the researchers to measure ply-by-ply delamination areas through the sample thickness. For example, C-scanning along with cross sectioning has been used in the paper [Dost, 1991] for observation of the delamination of sublaminates and for assessing the symmetry of a characteristic damage state.

Other advanced methods providing more detailed information about the material structure include X-ray photography and microtomography. X-ray photography records a series of 2D-images. A recent example of in-situ X-ray imaging (small-angle scattering) has been reported in paper [Deschamps, 2001]). Microtomography generates 3D-picture of micro-structure or 2D-slices. This X-ray transmission technique has been applied to a number of situations in material testing in paper [Maire, 2001]. Medium-resolution tomography allows one to assess samples with a relatively coarse structure of the order of tens of microns after a deformation event followed by unloading. High-resolution micro-tomography allows for in-situ analysis of materials with a finer structure, including metal-matrix composites.

Unfortunately, the X-ray-based techniques require a compromise between resolution focusing and exposure time. Therefore, these techniques do not allow an in-situ study of processes which are faster than of the order of seconds, i.e., these techniques are not applicable to high-strain rate processes. Usually, composite samples are analysed with this sort of techniques after the damaging event. For example, X-ray inspection has been used for an examination of matrix cracking and delamination in papers [Choi, 1990; Lagace, 1994; De Morais, 2005] and for an assessment of damage accumulation in paper [Zachariev, 2004]. X-ray inspection may be enhanced by computer tomography (CT) scanning which allows 3D-structure to be determined (such an enhancement was outlined in publications [Fink, 2001; Green, 2001]).

Summarising this review on the Ultrasound and X-ray transmission/scattering techniques, it can be concluded that while new methods for inspection of targets are being developed, including novel methods of restoration of the structure image inside a target (see, e.g., [Green, 2001]), C-scanning remains the main method for inspection of composites after impact (see, e.g., [Hosur, 2004c]).

Some novel NDE methods enable one to conduct the in-situ evaluation. Further advancements in ultrasonic inspection techniques include the use of Acoustic Emission (AE) phenomenon for the in-situ monitoring of composites subject to damage as shown in paper [El Guerjouma, 2001]. The method is base of the measurement of amplitude and the number of acoustic signals generated during deformation of a composite material, when ultrasonic waves in the material result in pulses of the acoustic energy detectable by AE transducers. The development of a methodology for comprehensive interpretation of AE signals for different modes of fracture is still underway. However, when a database of signal patterns has been collected for probable fracture modes, the monitoring method may become a reasonable alternative to the more expensive methods which are currently used. Similarly, acoustic emission (AE) from the flexure loading of samples subject to low velocity impact (up to 3J) was used in paper [Kwon, 1997] for evaluation of the impact damage. The samples were also C-scanned. The study demonstrated a correlation between the results of the acoustic scanning and the AE results for two CFRP material samples.

In paper [Kawaguchi, 2004], in-situ AE monitoring of a composite material was used. The study showed that damage initiation may start during the elastic part of the stress-strain response of a glass/epoxy composite under the uniaxial tensile testing. The damage initiation for indentation tests may accord with the maximal load or the first peak load for certain types of composite structure. The fatigue life of uniaxially loaded composite samples under indentation has been studied in [Kawaguchi, 2004]. It has been shown that different loading modes, resulting in different damage accumulation mechanisms associated with either delocalised or localised damage, are critical to the fatigue life.

Ultrasonic NDE studies, associating damage in a sample with the change of speed of the Lamb waves, have been conducted in papers [Rosalie, 2004; Toyama, 2004]. This technique employs a transmitter and receiver of ultrasound positioned at a distance from each other on a sample surface, so the acoustic waves (Lamb waves) propagating in the sample may change velocity and amplitude depending on a damage within the sample. Thus, in contrast to the C-scanning technique that inspects material in the through-thickness direction, the Lamb wave ultrasonic technique examines the material in the along-surface direction. Papers [Rosalie, 2005; Wu, 2005] suggest analytical methods for this technique, which allow a reconstruction of the damage areas. In the paper [Toyama, 2004], the C-scan technique is compared with the advanced Lamb wave technique enabling one to determine edges of delamination zones. It is argued that primary two-line scanning which uses a transmitter and receiver of the waves, is significantly more time-consuming than C-scanning. Also, delamination details (such as depth of the delamination, etc) cannot be determined with Lamb wave scanning. However, time delayed consecutive scanning may overcome some of these drawbacks, as is argued in the paper [Rosalie, 2004]. In paper [Bar, 2004], different (PVDF) gauges were used in order to measure acoustic emission using an artificial neural network approach as the analysis methodology. The objective of this study was the evaluation of several failure mechanisms (matrix cracking and local delamination) during tensile loading of GFRP samples.

Other novel methods of in-situ monitoring employ the principles of smart materials. For example, embedded sensors for monitoring damage in sandwich structural materials containing a honeycomb core have been employed in paper [Lestari, 2005]. This technique is based on a methodology of damage assessment using knowledge about the most probable deformation modes resulting in the damage. In paper [De Oliveira, 2004], optical fibres have been employed for in-situ monitoring: Fibre Bragg Grating (FBG) and Fibre Fabry-Pérot Interferometry (FFPI) were used in this study. The FBG technique is based on a photosensitive mechanism; the wavelength of a beam propagating in the optical fibre embedded or mounted on a sample may change with strain and temperature and hence this can be used for indications of the change. The strain and temperature sensitivities of this technique are coupled. The FFPI technique is based on the effect of changing position between the fibres' ends embedded in a material structure. This technique is sensitive to acoustic wave propagation through the FFPI gauge. Both techniques have their advantages and disadvantages. The advantage of the FBG gauge is that it allows a relatively simple demodulation of signals, facilitating interpretation of results. The disadvantages are that strain-temperature coupling is a feature of the technique, which masks the signal variation, and time resolution in transient processes is poor. The advantage of the FFPI gauge is a higher wave sensitivity, which makes it possible to use the FFPI technique in transient processes. The disadvantage is a complexity of the demodulation of signals requiring high-cost equipment, such as a laser. Some principles of signal processing applied to deformation and fracture modes for a composite have been developed and used in the paper [De Oliveira, 2004].

Piezoelectric gauges embedded in aluminium-epoxy GLARE material have been used in the paper [Rosalie, 2004] for the in-situ monitoring of damage during deformation of material samples during vibration. One way to decouple temperature and strain when employing the FBG technique is to use infrared technology, such as infrared thermography. Infrared thermography was used in DSTO (see [Krishnapillai, 2005]) for examination of the thin parts of aircraft when they are inspected for the presence of damage. A drawback of this technique is that it cannot be used for inspection of materials in the through-the-thickness direction.

Raman spectrometry may be used to study microstresses in samples. This is a technique allowing one to collect data for composite materials (see, e.g., [Colomban, 2002]). Stress induced Raman shifts are used in order to determine stress in fibres or other constituents of a composite if they are larger than several microns. This technique, however, requires thorough pre-calibration for the composite constituents. Also, cross sectioning of samples is necessary for the application of this technique, which may introduce micro-stresses and complicate the interpretation of results.

4. Impact against composite targets

4.1 Novel methods of testing: Plane wave testing

Methods for experimental evaluation of the impact response of composite targets involve observational and instrumented evaluation of the state of the target material. Among the methods of observational evaluation, optical methods are the most popular in studies of the material behaviour during impact (e.g., [Hammond, 2004]). These methods help identify failure mechanisms when observing the rear surface of a target (see [Tanabe, 2003a]), measure the fracture wave propagation in transparent composites by tracing the change in transparency (see [Bourne, 1997]) and in-situ evaluate deformation and fracture at the rear side of a target using the fine grid technique (described in paper [Rae, 1999]) for obtaining information about displacement of the grid marks at the distal side of the target.

In the area of instrumented methods of evaluation, new techniques are being developed in order to record material stress response during impact. The most direct method is stress measurement in the target's material by embedded gauges. However, this method is complicated by early destruction of the gauges. An example of using an indirect method (recording of response of a projectile instrumented with gauges) is reported in the paper [Bourne, 1997].

A novel technique is reported in paper [Starratt, 2000] based on the experimental assessment of target response to ballistic impact via measurement of projectile velocity during perforation of the target. The velocity is assessed from laser beam obscuration by the projectile with the beam being directed orthogonally to the projectile's direction of flight. The measurement facility is named Enhanced Laser Velocity System (ELVS). Laser obscuration data as a function of time are used for derivation of the projectile displacement-time data which are in turn used for evaluation of the target ballistic resistance and absorbed energy calculated from the assessment of attenuation of the projectile velocity. Effects associated with deformation of the projectile and with its non-ideal encounter with the target, such as tumbling and yaw, are not assessed. Quite considerable deviation of the calculated absorbed energy from what was expected is explained in the paper [Starratt, 2000] by these effects. Absorbed energies for Glass-Fibre Reinforced Plastics (GFRP) and Kevlar fabrics are evaluated in this paper with the ELVS technique.

Paper [Cepuš, 1999] reports on high-speed photography observations of the same ballistic impact event and compares these observations with the ELVS data (see [Starratt, 2000]). The impact of GFRP targets by conically nosed projectiles is considered. The time-displacement curves are converted into absorbed energy-time dependencies. The paper [Cepuš, 1999] does not however discuss possible complications resulting from inaccuracies in the assessment due to yaw and from transition of the target bending to perforation (the bending obscures the projectile-target assembly). The apparent obscuration caused by target displacement also complicates interpretation of the data. Another paper [Starratt, 1999] dealing with the same technique describes ballistic impact against a Kevlar fabric target while recording the velocity-time dependence by ELVS during impact by a blunt projectile. The records are used for calculation of the force and absorption energy. Because the technique evaluates displacement of the projectile, the assessed energy is not related directly to the energy absorbed by the target, so the assessed absorbed energy decreases unrealistically after the moment of perforation. Currently, despite the difficulties in record interpretation and accuracy/resolution issues, ELVS is one of the most advanced techniques for the in-situ measurement of target response during impact.

Emission spectrometry and high-speed visualisation are conducted in paper [Ramjaun, 2003] for an impact event. Emission spectrometry allows an evaluation of the temperature with a fibre optics probe that transfers emission radiation during impact to a spectrometer. The study conducted in this paper has revealed that the temperature at the point of impact is likely to be higher at oblique impact than at normal impact. The temperature measurement technique in transient events is still in its infancy because resolution and accuracy issues have not been properly resolved yet.

Ballistic impact by a compact projectile generates a complex stress state in a target, which makes it difficult to interpret the target's material response. In contrast, plane wave impact tests result in a uniaxial stress state in the target, which is easier to analyse. In addition, plane wave impact provides stress states that are not easily achieved in static and SHPB testing. The strain rate is higher during real ballistic impact than during an SHPB test and, therefore, plane wave tests better reflect the conditions of ballistic impact. The primary objective of plane wave impact tests is acquisition of data for equations of state that are necessary for modelling.

Equations of state are necessary for material models used in hydrocodes. Traditionally, an Equation Of State (EOS) takes the material response in the form of an average stress versus density. This is based on bulk characterisation at large deformations in contrast to the primarily shear characterisation at small deformations. Shear characterisation is used for the derivation of constitutive equations (see Section 3 in this report). If the shear characterisation is conducted in the uniaxial stress state, the bulk characterisation is usually performed under uniaxial strain conditions, which enables experimentalists to achieve large deformations and a significant densification.

When an EOS is aimed at the most complete characterisation of material state, a material description is needed that would give the stress response of material to every component of strain at large deformations (see [Godunov, 2003]). To simplify the description, modern hydrocodes typically deal with the volumetric (bulk) response processed by the EOS and the deviatoric stress (shear) response processed by the constitutive equations. The EOS data are usually obtained in the form of the shock adiabat (the Hugoniot) that links pressure with density behind the shock front from the shock speed-material velocity dependence, using the Rankine-Hugoniot relations. This derivation neglects the nonstationarity and complex structures of shock waves in advanced materials, such as composites and porous materials. For example, the nonstationarity of shock wave formation and the complex structure of shock waves in porous materials have been considered in papers [Butcher, 1974; Resnyansky, 2004b]. The structure of the shock wave in a graphite-epoxy composite and its evolution has been traced with manganin gauges as reported in papers [Borzilovsky, 1994; Boteler, 1997]. In particular, for foams (and porous materials in general) it is almost impossible to separate the acquisition of the EOS from the acquisition of the constitutive equation. Because the Rankine-Hugoniot relations operate with an ideal shock wave, the plane test data are just the first approximation of the material response. This approximation is probably the only one that is possible with current state-of-the art experimental methods.

Plane wave tests with porous materials are not rare but polymeric and metallic foams are not frequent subjects of plane wave tests due to a number of difficulties emerging in the testing of cellular materials. One of the difficulties is the boundary condition effect, because these materials are sensitive to collapse initiation, which usually begins on the specimen's free boundary. Special design of the specimen constraints has been used in the paper [Baker, 1998] in order to start the material collapse inside the bulk of material not affected by the boundary free surface (design of the constraints is discussed later in Subsection 5.4). Aluminium and stainless steel honeycomb materials have been tested using a heavy impactor of 50mm in diameter that impacts material specimens of the same diameter (the impact velocity is nearly 100m/s). Velocity gauges are used for evaluation of displacement of the impactor and a load cell attached to a sample is used for evaluation of the force acting upon the sample. When comparing the results with the static tests described in subsection 3.4, rate sensitivity has been observed for the compaction stress. An interesting feature of the dynamic material response is stress relaxation in the second half of the compaction stage, which was not observed in the static tests.

The tests conducted in the paper [Baker, 1998] are not real plane wave experiments because they do not evaluate the wave effects occurring in the samples during their deformation. An example of real plane wave testing of a foam material has been published in paper [Kipp, 1999]. In this study, the Hugoniot data are obtained for polyurethane foam using gas gun experiments. The methodological issues are similar to those in SHPB testing where the signal, being recorded by gauges, is very low and it is comparable with the electronic noise. Therefore, special sandwich set-ups (the shock reverberation technique described in paper [Lysne, 1969]) are used in order to restore the response from a porous material (see [Resnyansky, 2004b; Salisbury, 2000]). Paper [Kipp, 1999] has reported a direct measurement with an interferometric system (VISAR) that records the free surface velocity of a target assembly. The target assembly is subject to plane impact and contains a foam sample that is backed by an aluminium witness plate. Velocity in the foam is recalculated using the jump conditions and tabulated material properties for the reference material (aluminium). Paper [Salisbury, 2000] reported both records from PVDF pressure gauges and velocity profiles from an interferometer taken during the impact of foam samples sandwiched between aluminium and PMMA plates. In this work the sandwich target was loaded by explosive products through the proximate initiation of an explosive charge. The data were supposed to be used for calibation of the equations of state for the foam. It should be noted that the major drawback for proper calibration is the absence of information on input load to the sandwich target; only the pressure/velocity records after propagation of the shock through the target have been taken and reported. However, the loading pulse cannot be confidently assessed with the selected method of loading.

Traditionally, the shock response characterisation of conventional materials is obtained with plate impact tests. However, methodological difficulties associated with such properties of composite materials as brittleness, strong anisotropy, and relatively weak interlaminar strength, do not allow experimentalists to conduct extensive plane wave studies. Examples of such studies are not frequent. However, when composites have been tested with a plane impact facility, their behaviour resembles the behaviour of conventional materials in many aspects. For example, damage accumulation linking the peak stress at damage with the stress pulse duration has been observed for a 3D carbon/carbon composite in paper [Goeke, 1975]. The observed damage accumulation is qualitatively the same as for conventional materials at the onset of spallation.

However, composites are a highly anisotropic and non-homogeneous material and the influence of inhomogeneities on the velocity was clearly noticed in paper [Héreil, 1997]. This study observed multiple spallation traces, corresponding to delamination, when recording by VISAR interferometry the free surface velocity of a composite target at different impact velocities of a flyer plate. Hugoniots for composite materials were obtained routinely in the recent decade. An example published in paper [Fujii, 2001] is the Hugoniots for a carbon/carbon composite obtained with PVDF gauges embedded in an assembly containing the composite and impacted by a flyer plate launched by a gas gun.

An early attempt at plane impact testing of a graphite/epoxy composite has been undertaken in paper [Fyfe, 1988]. In this study, composite plates were loaded by aluminium flyer plates driven by exploding foils. The small thickness of the impactors resulted in difficulties of interpretation of the target plate delamination due to the uncontrolled loading pulse and a high roughness of the target plate (with respect to the flyer plate thickness). A detailed study of the delamination of a glass-fibre reinforced composite under plane wave impact was conducted in papers [Boteler, 1997; Dandekar, 1998]. An ultrasonic study enables the authors to reveal the tetragonal symmetry of the material with the elastic properties expressed by six independent elastic constants. A gas gun has been used for the tests instrumented with the VISAR free surface velocity measurement system. The study observes a velocity drop that usually corresponds to spallation in a tested material; in the present case, the velocity drop is associated with delamination in the composite material. For the purpose of the study, composite sample plates were obliquely impacted at velocities from 20 to 80 m/s. Elastic constants determined from these tests were used for evaluation of the delamination stress derived from the recorded free surface velocity. The test results showed that delamination occurs at 0.06 GPa for the case of the normal impact and at 0.007 GPa for the impact with an obliquity angle of 26°. It is concluded, therefore, that delamination is primarily associated with shear. Oblique plane wave testing at relatively low velocities of impact (tens of meters per second) and observation of the wave structure that was split into several waves has also been performed in paper [Sve, 1974]. A study on the wave attenuation in a composite has also been conducted in paper [Lundergan, 1972]; the study exhibits the complex structure of waves in this material, where the test assembly included a composite with the material symmetry axis misaligned against the loading direction.

In paper [Zhuang, 2003], a study of wave structure has been undertaken, using VISAR interferometry for free-surface velocity measurement and embedded gauges for stress measurement. Targets subject to high-velocity plane impact were PMMA/stainless steel and the PMMA/glass layered composite assemblies. The objective of the study was determination of the width of the shock wave generated after plane impact of the target assembly by a flyer plate. The paper concludes that the shock viscosity associated with the shock width is much larger (this is expressed by the quadratic function with an argument of the stress behind the shock) than for a conventional reference material (expressed as a fourth order power law). This width enlargement is associated with wave dissipation on the fibre-matrix interfaces. The paper [Zhuang, 2003] also makes a surprising conclusion that the shock speed in the composite is unusually low, lower than the speeds in the constituents. This conclusion may result from the fact that several points have not been clarified: i) the Hugoniot for the heterogeneous material is not derivable from the Hugoniots for the constituents due to the availability of the fibre-matrix interfaces, which prevents calculation of the compressibility of the composite at high pressures from the compressibilities of the constituents; ii) the dissipation on interfaces forms a wave pack that has a high-frequency component which cannot be traced with the technique employed in the paper; and iii) the wave width is comparable with the layer thickness and the mixture rule is not applicable – the mixture rule for composite works well when the size of inclusions is much less than the wave width.

Blast loading is complementary to plane impact loading and an alternative to uniaxial strain SHPB loading because it provides a relatively even distribution of load over the target area. Thus, a uniaxial strain state in material is achieved if the charge is initiated in the open air or underwater at a significantly large stand-off distance. However, the stress level in material under such a load is rather low (see [Librescu, 2004]) and it does not reach the range that is characteristic for ballistic impact. If an explosive charge is initiated in close contact with a composite-containing target then pressures comparable with the ballistic impact range could be achieved. However, a fairly large area of the target needs to be covered by the explosive load and the charge should be initiated in a synchronised instrumentation-controlled manner, otherwise the data cannot be clearly interpreted because cracks and delamination occurring at the event are obviously caused by the variability of the loading over the target surface (see, e.g., [Franz, 2002]). Studies on blast loading of cellular materials are even less common than studies on the blast loading of composites. An interesting feature of the blast response of a foam-containing target has been reported in paper [Hanssen, 2002a] where the momentum transferred to a ballistic pendulum increases when the target surface of the pendulum is covered with a foam material (an aluminium foam). The presence of an aluminium skin does not change this trend. This phenomenon is substantiated by the deformation of the surface acceptor (the foam or the skin in the case of the sandwich set-up), thus decreasing the energy and momentum dissipated into the environment.

4.2 Theories employed for analysis of the composite response to impact

Numerical analysis is a powerful tool with a high predictive potential. However, a computer program can only process the modeller's representations about the physics of the process being simulated. Therefore, a poor understanding of composite behaviour at impact cannot result in a satisfactory description of the composite target response if the models used fail to represent physics of the process. The previous Section and subsection 4.1 outlined the data that are necessary in order to characterise material. The characterisation data are used by a model/theory as input. In general, the theories have to take into account a number of physical factors from the conservation laws down to the constitutive interaction and behaviour of the composite constituents. The level of detail taken into consideration provides the corresponding level of description. For example, it is unreasonable to look for an answer as to how fibres interact with a matrix if we consider a composite as an anisotropic elasto-plastic material, because the elasto-plasticity model ignores the material's micro-structure.

Depending on the purpose of a theory/model, several major levels of description for composite and cellular materials are circulating in the literature: 1) material as a set of interacting components; 2) material as a homogeneous anisotropic medium with mechanical properties averaged over the representative volume; 3) material as a homogenised medium with a micro-structure that is described by micro-level analysis incorporated into the higher-level phenomenological description; and 4) material as a structural set of components which are described on a meso-level (the hierarchical description). At first glance any composite behaves as an anisotropic material. The micro-structural response of composites (interaction of constituents, development of micro-stresses) is most obvious at the damage and fracture stages of deformation. A detailed review of the modelling approaches associated with brittle fracture behaviour will be conducted in the next subsection and a review of the approaches related to viscous damage in subsections 5.6 and 6.7.

Simple instances of the first modelling approach have been realised in papers [Chen, 2004a; Mines, 2004] where analytical formulas are used that are based on the Riemann problem solutions (the solutions of the jump conditions that connect the parameters of constituents of a composite laminate loaded by a shock wave where the laminate is represented as a periodical structure). Wave scatter and attenuation can be evaluated with those formulas thus allowing an assessment of the impact resistance and energy absorption of the laminates. A more complete illustration of the first approach is a general theory developed in paper [Williams, 1997], which enables modelling of a composite with two constituents (discrete number of layers), using different properties for each of the two constituents. The constituent descriptions can be complemented with an interface condition allowing debonding. A similar approach is employed in paper [Sen Gupta, 2005] when modelling a 3D carbon/carbon composite subject to plane impact.

Another example of a numerical realisation of the first approach is published in paper [Duan, 2005a]. In this paper, a plain-woven fabric is represented as a material with meso-structure, where the lowest structure level (yarn) is considered as a homogeneous orthotropic material simulated within the DYNA modelling approach. This approach [Duan, 2005a] and similar ones consider the mechanical properties of a composite as algebraic combinations of the constituents' properties. This approach can be realised in the assumption of perfect alignment of the constituents, ideal bonding, and consistent geometrical parameters through the whole composite. Therefore, for real-life composite material one of the concerns is the uncertainties in properties and geometrical parameters of the constituents. Deliberate introduction of such uncertainties in a mathematical way was explored in paper [Rao, 2004]. This paper has simulated several simple loading set-ups for a unidirectional composite, using the fuzzy approach (randomisation of operations and data).

The second modelling approach treats a composite material as homogeneous anisotropic material. An attractive feature of this approach is its simplicity. Some publications completely ignore the internal material structure. This simplification might be reasonable in the case of composite response to hyper-velocity impact, when the material compressibility in selected directions dominates over micro-structural effects. This approach is employed for a quite wide range of impact velocities. For example, paper [Fujii, 2003] simulates the wave arrival at the rear surface of a composite target (for evaluation of the onset of damage), using the AUTODYN hydrocode. An elasto-plastic material model is used, which has been validated for simulation of conventional materials under static loads. The model was modified in paper [Fujii, 2003] by the use of an equation of state with the compressibility characteristics taken from plane wave tests (the Hugoniot data).

An isotropic elasto-plastic model was used in paper [Lim, 2003] for prediction of the residual velocity of a spherical projectile after ballistic impact and penetration of a fabric armour. The DYNA hydrocode was employed in this simulation. The modelling of perforation was conducted in this paper with the erosion option of DYNA. The erosion subroutine eliminates the finite elements of the computational grid of a target, when a failure strain (an artificial numerical parameter that is convenient for prevention of a computational grid from excessive deformation) has been achieved. Formulas used in the paper [Lim, 2003] for the failure strain have been reported in detail in paper [Shim, 2001]. As was described in subsection 3.3, this failure strain, which was taken from [Shim, 2001], was associated with the start of release from the load applied (a limit strain in the stress-strain response obtained with a SHPB facility). It was noted in subsection 3.3 that this strain is not necessarily associated with a failure. In the model used in the study [Lim, 2003], the failure strain, the elastic modulus, and yield stress of the fabric are fitted to the SHPB high strain rate data for this material (see [Shim, 2001]). The failure strain dependence introduces new fitting parameters. It should be noted that an integral characteristic (residual velocity of the whole projectile) is required to be predicted. In general, the residual velocity obtained from the DYNA simulation might be close to experiment over a fairly wide range of change of this code-related failure strain parameter.

Therefore, the inclusion of rate sensitivity in such a simplified model is excessive, keeping in mind the large number of fitting parameters used.

A MAT_COMPOSITE_FAILURE_SOLID material model from the DYNA material database is employed in paper [Fawaz, 2004] for simulation of the target response to ballistic impact. A composite material is considered to be an elastic anisotropic (orthotropic) material with failure (the material erosion) at a critical stress. Similarly, a rate sensitive material model with transverse isotropy is used in paper [Shintate, 2004]. In this paper an SPH code uses this model to simulate the dynamic behaviour of a graphite/epoxy laminated composite during high-velocity penetration. It should be noted that the structural effects of composite materials are very difficult to discriminate even when the composite response to a moderate velocity impact is simulated with the help of a Lagrangian code. The present calculation [Shintate, 2004], which employs the hydrodynamic SPH method, confirms this difficulty. A lack of response variability associated with the nature of the composite is noticeable when the material response is analysed with this method under high-velocity impact.

Implementation of a more complex anisotropic model in AUTODYN, which has been conducted in paper [Clegg, 1999], has required decoupling of the stress response of a composite material into volumetric and deviatoric stress responses (to make the model fit to the philosophy employed in the hydrocodes). Composite materials (Kevlar and Nextel fabric) are considered to be homogeneous within the anisotropic elasticity. Material compaction, associated with possible porosity, is treated as an increase of the limit stresses (that is actually the boundary of the plasticity surface in the stress state space) in the hardening fashion. Tensile failure is taken into account by the reduction of the material stiffness to zero when failure has occurred. The failure criterion is formulated with a specially introduced 'damage' parameter (a pre-selected fitting constant).

For many composites with polymeric or resin matrix the overall behaviour is inseparable from the rheological behaviour exhibited by the matrix. Easily achievable irreversible deformations of the matrix material and thus induced micro-stresses influence the composite response. Understanding of the necessity to take the rheology into account has been demonstrated in papers (see, e.g., [Rémond, 2005]) which pay attention to the rate-sensitivity of composites with polymeric or resin matrices when testing these composite materials. Involving the material rheology in the analysis of the viscoelastic behaviour of a composite and the evaluation of micro-stresses that are caused by the incompatibity of the rheological properties of constituents is an interesting task being realised in papers [Lévesque, 2004; Resnyansky, 1995a; Resnyansky, 1997a]. A viscoelastic model with isotropic hardening under simple loading (the loading along a constant direction in the stress space) has been considered in paper [Kawai, 2003] for a CFRP.

The third modelling approach arose from the attempts of many authors to approximate a composite as an anisotropic elastic material, using laws which are similar to the mixture rules for multi-component materials. Using these laws, the elastic modulii of a composite have been derived from the modulii of constituents, resulting in several popular approximations such as the Voigt or Reuss estimates of the elastic modulii (see [Tsai, 1980]). More sophisticated estimates refer closer to the structure of a composite as shown in monograph [Christensen, 1979]. An example of the building up of the stiffness matrix of an elastic material (that simulates a woven fabric, which is similar to the material modelled in paper [Duan, 2005a]) with the homogenisation approach has been conducted in paper [Tanov, 2001] in order to incorporate the elasticity model in DYNA. Publications [Resnyansky, 1995a; Resnyansky, 1997a] develop a homogenisation approach for unidirectional and laminated orthotropic structures. The elastic modulii of the composites are obtained from the elastic modulii of the constituents using a procedure that analyses the constituents' interaction in the principal material symmetry directions. Similar procedures are known as the bound estimates and they may deal with an evaluation of a bulk material from the properties of a representative volume by integration (see [Böhm, 2004]). Special application of several homogenisation techniques to the calculation of the elastic modulii for multi-phase composites is noted in paper [Pierard, 2004]. Within the same homogenisation approach, the elastic modulii for a carbon/carbon composite (this material has inclusions of a preferable orientation according to a given distribution) have been calculated in paper [Piat, 2004].

However, an extension of homogenisation techniques into the range of irreversible deformations is of most interest for simulation of the high-velocity impact response of composite materials. Application of a universal algorithm to the process of homogenisation of a periodic composite structure has been described in paper [Luo, 2005]. As mentioned before, the inclusion-matrix interaction due to different material properties of the constituents is the main reason for the interfacial micro-stresses induced during deformation. For viscoelastic composites (composites with polymeric or resin matrices), homogenisation approaches dealing with the material rheology have been adopted in papers [Lévesque, 2004; Resnyansky, 1995a; Resnyansky, 1997a]. Micro-stresses can be derived from micro-mechanical equations (such as the equations that link parameters of fibres with parameters of a matrix, which have been used in the paper [Resnyansky, 1997a]). Otherwise, the micro-stresses can be considered as constitutive parameters for evolution (constitutive) equations adopted for these parameters (see [Goldberg, 2002]). A homogenisation approach derived in the paper [Resnyansky, 1997a] has allowed the authors to progress in both directions – to link the parameters of the constituents and to derive constitutive equations for unidirectional and laminated composites where the parameters of the constitutive equations are micro-stresses. In addition, the model has been generalised for the case of finite deformations (see [Resnyansky, 1995a]). The study [Resnyansky, 1997a] has analysed theoretically SHPB tests for off-axis loaded composites and shock wave propagation in laminated composites when the material axis is not aligned with the loading direction. The regime of variation of the stress response with strain due to fibre rotation was observed during uniaxial stretching of a sample (the stress response of the constituents has no variations, i.e., the yield limit is constant for the constituents). Simulation of impact tests exhibited a three-wave structure due to the same effect, which was confirmed with available experiments [Lundergan, 1972; Sve, 1974].

Many of the material models ignore the effect of changing the direction of material anisotropy. Typically, these models assume that the shear deformations are small and therefore, the material symmetry direction is not changed during the deformation. However, under high-velocity impact conditions this is not true. The variation of the material axis direction (so-called spin) may affect the numerical results significantly, specifically for the cases when off-axis loading occurs. In recent years, novel models have been developed, which consider the spin effect which is associated with irreversible deformations in the matrix or in both the matrix and fibres. A phenomenological description of this effect outlined in paper [Spathis, 2004] is based on the alignment (relaxation) of the spin to the principle material symmetry directions. The model described in papers [Resnyansky, 1995a; Resnyansky, 1997a] involves the micro-structural analysis of the constituents' interaction followed by homogenisation, which results in a constitutive equation for the spin. Presently, the majority of novel models dealing with finite deformations take the spin effect into account.

The fourth modelling approach is an hierarchical extension of the homogenisation approach which has been originally applied to several (usually two) constituents of a comparable scale. Recent examples of this approach look at the scale hierarchy during a homogenisation (see, e.g., [Dendievel, 2001]). Two homogenisation levels are considered in paper [Jadhav, 2003]. They include, firstly, the micro-mechanics of a unidirectional lamina processed with a finite-element procedure and, secondly, a combination of several differently oriented laminas into a composite, using a numerical algorithm as the second homogenisation level.

A multi-level homogenisation (four levels for a woven fabric) has been conducted in paper [Kwon, 2001], resulting in a finite-element numerical model for an elastic material (effectively, the homogenisation has been applied to the elastically behaving constituents). Similarly, a generalised method of cells extends by periodicity the elastic properties for a bulk material from the properties of a cell that is contained in a repeatable (periodical) structure of woven polymer matrix composite (see [Bednarcyk, 2003]). Several groups of cell types are observed and classified in the paper [Bednarcyk, 2003]. These cells combine the whole structure of the material and the elastic properties of each group are derived from the micro-mechanical analysis of the cell's behaviour. A hierarchical homogenisation has been considered in paper [Harrison, 2004] for a sample of a woven polymeric composite under simple loading (shear against shear angle). The rheology of the constituent (the matrix) has been taken into account, using a simple viscoelastic model.

4.3 Theories employed for fracture analysis of the composite response

Fracture of composite materials can be modelled either on the micro-structure level (e.g., taking the fibre-matrix interactions into account, analysing effect of individual cracks, etc.) or in the phenomenological manner (averaging material properties, homogenising the material structure, assessing damage as a continuous parameter of material). The phenomenological description of fracture can also be done with use of a traditional linear fracture mechanics approach, as it will be shown in this subsection. A review of relevant experimental data available in the literature was provided in the previous Section.

Linear Fracture Mechanics (LFM) concepts (the fracture toughness, stress concentration factor, *J*-integral) have been fruitful for a long time for structural design, optimisation, and assessment of conventional materials under static conditions. However, transferring of the concepts to specific geometries, complex loading, dynamic conditions, and, particularly, to composite materials brings up the question of validity of the LFM concepts within a complex environment. Examples of using the LFM principles in phenomenological computations are few in number, even for the isotropic materials (see, e.g., [Ravichandran, 1995; Sandhu, 1982]). Due to the lack of experimental data on crack propagation in a complex environment, the data on isolated cracks can only be indirectly interpreted and processed by means of theoretical modelling. For example, only a few fairly recent attempts to take into account material deformation due to cracking, using the LFM approach have been undertaken (see, e.g., [Mazars, 1986; Ravichandran, 1995; Rots, 1989]).

Cracking is a dynamic process. Straightforward approaches can be used for the simulation of cracking in dynamic processes. Kinetic principles of viscous fracture developed in papers [Curran, 1977; Seaman, 1973] consider accumulation and growth of damage occurring in ductile materials. This viscous type of fracture does not suit the situation of debris formation in brittle materials under high-velocity impact, where the large energy consumed by a material results in non-stable cracking. However, some mechanisms of viscous fracture may occur at the onset of fracture formation. A basis for consideration of fracture onset might be the damage accumulation criterion derived in papers [Steverding, 1971; Tuler, 1968]. Paper [Merzhievsky, 1995] assumed that the delay time of crack start is determined from a semi-empirical time-dependent criterion in the general form:

$$\int_0^t \left(\sigma - \sigma_0\right)^n dt \geq J_0 \; ,$$

where σ_0 is a threshold damage accumulation stress, n is a material constant, and J_0 is a damage accumulation threshold (the stress impulse for failure in the case of $n = 2$). This criterion was used in papers [Merzhievsky, 1995; Resnyansky, 2002b] in the following kinetic form for a variable j of the accumulated damage:

$$\frac{dj}{dt} = \left(\sigma - \sigma_0\right)^n \; .$$

Then the criterion takes the form $j \geq J_0$ and fulfilment of the criterion results in a crack that starts travelling with a given empirical velocity depending on the stress state. This criterion has been applied in the split-element method that introduces the crack surfaces into a computational grid. Control of propagating cracks, their coalescence and dividing a piece of material into fragments is the main difficulty of programming and application of the split-element method in a code. Numerical methods based on the Godunov scheme with the adaptive grid method have been applied to the problem of perforation at high velocity impact in paper [Merzhievsky, 1985] and to several problems of high velocity and hypervelocity impact – in paper [Merzhievsky, 1995]. The main feature of the adaptive grid method is that computation is conducted in the Eulerian coordinates with exterior Lagrangian boundaries. The main difficulty in the realisation of the split-element method in the papers [Merzhievsky, 1985; Merzhievsky, 1995] is an extension of the adaptive grid method to the case of disconnected grids. This modification enables a crack (new Lagrangian free boundary) to be introduced in the computational grid as shown in papers [Merzhievsky, 1992b; Resnyansky, 2002b]. This approach has further been developed for the 3D-case and implemented in Lagrangian DYNA hydrocode in paper [Resnyansky, 2002b]. Isolated cracks with a pre-determined direction, allowing the authors to omit the above-mentioned difficulties, have been calculated for a quasi-static case in paper [Wilkins, 1977] and for the case of high-velocity impact in papers [Chen, 1975; Sedgwick, 1973].

The dynamic character of the cracking process forces a fracture to be represented as a non-equilibrium process. The kinetic approach associated with the dynamic nature of a fracture may be applicable to the phenomenological simulation of fracture. This suggests the potential of incorporation of the classical fracture theory in a constitutive model which makes use of known dependencies of the fracture toughness on strain rate and temperature. A similar approach has been exploited by the well-known rate sensitive viscoelastic models which incorporate experimental dependencies of yield stress on strain rate and temperature into the models.

The above-described direct fracture modelling approaches connect crack formation with the computational framework (a grid). Incorporation of micro-structure or phenomenological approaches into a model framework requires the use of fracture concept within the thermodynamics formalism. Regardless of the approach selected, a model is required in the closed form. Problems associated with the impact behaviour of samples in dynamic fracture experiments as well as prediction of the behaviour of composite components in aircraft and space equipment could be solved with such models. The ultimate objective of such an investigation would be the construction of a model combining the universality of the continuum mechanics models with a detailed description of fracture behaviour. This leads to a possibility of tailoring the mechanical properties of composite structures, similar to the studies in [Annin, 1990; Tanedar, 1989].

Two major approaches are most popular for the description of fracture of both conventional and composite materials. The first considers fracture from the micro-mechanical point of view, which analyses behaviour of an individual crack using principles developed from Linear Fracture Mechanics (LFM). LFM concepts such as the stress intensity factor, fracture release energy and, in the inelastic case, the *J*-integral have been used in a great number of papers (see, e.g., [Bandyopadhyay, 1990; Karihaloo, 1989; Lin, 1993; Sih, 1962]). An example of a direct implementation of a crack into a finite-element grid has been described in paper [Kelley, 1977]. In this work, the stress field around the crack was governed by the stress intensity factor. This implementation took into account the stress singuliarity in the vicinity of the crack tip, employing the LFM approach. The second (alternative) approach does not consider the micro-behaviour of cracks and the fracture process is assessed by its effect on the phenomenological response of material. For example, such phenomenological theories [McLaughlin, 1972; Tsai, 1971] construct theoretically and experimentally the fracture/ strength surfaces in the stress space, similar to the yield stress surfaces in classic elasto-plastic theories. In the case of composite materials, the fracture processes are much more complex due to a possibility of debonding/delamination and the interaction of constituents. The micro-mechanical approach to composites also deals with the analysis of separate fibres in a matrix (for laminated structural materials – with the analysis of a small number of layers as shown in papers [Bruno, 1990; Hashemi, 1987; Williams, 1994]). In addition, this approach considers problems of fibre pull-out, push-out and debonding [Caruso, 1989; Hsueh, 1993; Markworth, 1993], adhesion and delamination [Chai, 1993; Fife, 1987; Masters, 1989; Reifsnider, 1977], stress transfer [Kim, 1994] and fibre-matrix interaction [Foye, 1973; Fukahori, 1993; Kim, 1994].

Within the micro-mechanical approach, the failure criteria for various fracture models can be associated with criteria derived in LFM terms, for example, the stress intensity factor. Such a criterion can be derived because of the connection of the stress intensity factors for different load modes with the remote stress state. The connection of the factors K_I, K_{II} into a single criterion is the subject of a number of papers [Nallathambi, 1986; Sih, 1974]. For LFM concepts related to the inelastic behaviour of composites before the fracture onset, the phenomenological (σ,ε)-response can be associated with fracture toughness due to the connection of the *J*-integral with the (σ,ε)-diagram of the damaged (notched) samples as was shown in a number of papers [Nait-Abdelaziz, 1987; Rots, 1989]. In turn, fracture toughness deals with the micro-mechanical analysis of the fracture process. This link of the fracture toughness with the stress response can be grounded on the continuum damage (the damage accumulation) model of the softening of material as derived in paper [Bandyopadhyay, 1990]. In this case this link may look inconsistent and self-contradictory but in fact, the damage process is simply separated into two levels: macro-damage (an isolated crack of brittle type fracture) and micro-damage (a continuum of micro-cracks of viscous type damage).

The thermodynamics of the process of fracture is complemented by energy release due to the damage or cracking, which should be included in the energy balance equation (the thermodynamics identity). Decomposition of the consumed internal energy of the material element into the summands, which correspond to specific processes during the material deformation and fracture, has been used for a long time in the mechanics of fracture of homogeneous and composite materials (see, e.g., [Beaumont, 1974; Schapery, 1991; Sih, 1974]). Usually, the energy contribution associated with fracture takes the form $G \cdot dA$ in the thermodynamic identity:

$$T \cdot dS = de - \sigma_{ij} \cdot d\varepsilon_{ij} + G \cdot dA \,, \tag{1}$$

here G could be treated as the energy release rate and A is the specific surface of a forming crack. It should be noted that A is an "effective" characteristic because it is associated with the "unloaded" state of material with respect to the stable pre-cracking (along the blunting line of the envelope of the fracture resistance curves, so-called the R-curves, crack growth is classified into the stable and unstable phases and the latter is typically associated with dynamic crack propagation).

To close the thermodynamical identity (1), the rate of crack growth should be determined. Thus, the mechanism of crack growth has to be analysed, and the form of the dependence F that is proportional to the rate of crack propagation has to be selected. This dependence can be chosen in the form of a kinetic equation. As an example, the following dependence can be proposed

$$\frac{dA}{dt} = F \ ,$$

where d/dt is the material derivative. The most obvious variant of selection for the function F is:

$$F = k \cdot G^n \ .$$

The fracture mechanisms and growth rate equations of this type have been analysed and selected in a number of papers (see, e.g., [Mindess, 1985; Shah, 1986]). Such a selection of the function F is convenient because: i) its form can determine the crack initiation (it may be zero if $G < G_{crit}$ and works elsewhere, e.g., during damage accumulation); ii) it can locate the direction of crack propagation (e.g., the diagonal direction, according to the maximum stress principle, if the crack growth is stable, and the normal direction to the direction of load, if the crack growth is unstable); and iii) it can take into account various mechanisms of damage (e.g., a mechanism based on the extremum of the strain energy used in paper [Sih, 1985] or a mechanism based on the fracture toughness principle). Consideration of fracture from the thermodynamical point of view was conducted in paper [Schapery, 1991]. The energy release rate at fracture is taken into account in dynamic conditions in papers [Mclay, 1978; Mindess, 1985; Schapery, 1991; Shah, 1986] and the intensity factors in modes I and II are linked into one criterion in papers [Sih, 1962; Sih, 1974; Williams, 1976]. An advantage of the kinetic approach is its universality and the possibility of using it in dynamic (impact) conditions. Introduction of tensorial characteristics in (1) is also possible (see, e.g., [Mazars, 1986; Rots, 1989]) in order to embrace the consideration of fracture modes (especially mixed ones) as realised in paper [Hashemi, 1987].

An alternative phenomenological (continuum mechanics) approach considers the damage state as a continuous distribution of micro-cracks (and, if necessary, macro-cracks). The phenomenological approach could be applicable to composite structure as well since the theories of anisotropic elasticity and elasto-plasticity (see, e.g., [Sun, 1973]) consider the yield limit as a loss of bearing capacity, ignoring the composite microstructure. The main objective of this effort is the use of available finite element codes developed for anisotropic media in order to simulate the composite's behaviour made in papers [Foye, 1973; Kawata, 1981; Landa, 1988; Sandhu, 1982]. However, the omitting of microstructural details in these theories is the most vulnerable issue. Phenomenological approaches in theories dealing with composites have been reviewed in subsection 4.2. Phenomenological approaches in damage modelling will be reviewed in more detail in subsection 5.6 for the case of quasi-static loading and in subsection 6.7 for the case of dynamic loading.

Briefly summarising, in the static case the phenomenological approach for damage has been used early in the construction of the failure surfaces, similar to the yield surfaces in the theories of plasticity. Paper [Guntze, 1997] derives general fracture criteria for unidirectional composites under static loads and an attempt is made to take into account structural and material properties via the invariants of the stress tensor. The material is considered from a phenomenological point of view (the micro-structure of the material is ignored). Referring to the thermodynamics of damage outlined in this subsection, an illustration of how to construct a failure surface in the quasi-static case employing a kinetic approach is shown in paper [Resnyansky, 1995]. A problem considered in this paper calculates the failure surfaces for both uniaxially stressed and uniaxially strained states at various strain rates and the composite fracture is considered in the approximation of perfect bonding and continuous (undamaged) fibres. These calculations have established that effects associated with off-axis loadings are stipulated by micro-mechanical peculiarities of much higher order and should be considered more thoroughly. Similarly, the thermodynamics approach was employed in paper [Tushtev, 2004] for derivation of an anisotropic failure stress surface from a potential which depends on the strain energy. Thus, the anisotropic failure approach for composites just expands the anisotropic plasticity model.

A specific area of phenomenological modelling is associated with the development of homogenisation procedures. One of the first papers [Hashin, 1964] on this subject was devoted to derivation of the modulii of elasticity for a fibrous composite, aiming at the use of this information in anisotropic theories. At present, such considerations for composites, which incorporate material microstructure into macro-mechanical models, are quite widespread (see, e.g., [Kim, 1992; Resnyansky, 1995a; Sun, 1968; Taliercio, 1995]). Similar studies are being developed extensively because a successful outcome would give an opportunity to predict and optimise properties of composite and hybrid materials, using the properties of constituents. Micro-mechanical approaches based on a description of the behaviour of constituents (a fibre in matrix) in composite materials of various types are stated in papers [Hashin, 1964; Nikkel Jr., 1990; Shah, 1988]. The homogenisation principle could also be applied to damage analysis. The debonding of a composite at the macro-level has been considered in papers [Birger, 1989; Jackson, 1966; McLaughlin, 1972; Taliercio, 1995]. Debonding exhibits the macro-behaviour of a composite most clearly in off-axis conditions as shown in papers [Birger, 1989; Jackson, 1966]. An analysis of how the inclusion's size affects the load-response macroscopical behaviour at different strain rates has been conducted experimentally in paper [Sierakowski, 1971].

4.4 Theories employed for analysis of the foam response to impact

Foams and cellular materials in general combine properties and features of materials of different kinds, namely, solids, porous materials and composites. Therefore, the behaviour of these materials is extremely complex and universal theories do not exist. Generally, the stress-strain response of foam materials is characterised by minimal elastic regions of the stress-strain curves and these materials behave non-linearly during compression. Usually, the behaviour of foams is close to the behaviour of porous materials. Three deformation stages are realised during material compression: elastic response (this stage is negligible for a foam with weak cell walls and for porous materials such as sand this stage may be absent); compaction during which the bulk of the deformation energy is being absorbed; and a densification stage (sometimes, it is called the strain hardening) during which the material is being compacted and starts responding as a solid (this classification of foam behaviour was outlined, for example, in paper [Song, 2005a]). Therefore, the volumetric-deviatoric decoupling of the stress response (this decoupling is common for conventional materials and composites) is difficult for cellular materials, where the constitutive equation related to the deviatoric response is actually merged with the equation of state related to the volumetric response. Nevertheless, an attempt to employ the traditional modelling approach by decoupling the deviatoric and shear response has been undertaken in paper [Zhang, 1998] where the von Mises type flow rule has been used with an elliptic failure envelope in the stress space, which combines the pressure and shear stress (the von Mises type response). The power constitutive relation for the plastic strain rate has been used in order to fit the numerical results to hydrostatic, shear and uniaxial tests at different strain rates and temperatures. It should be noted that the model demonstrated a capacity (in fact, the coefficients of the constitutive relation) to fit the results to the experimental data; however, the model was not verified against independent experimental data.

Foam and honeycomb materials manifest their peculiarities most clearly under compression. A simple representation of the compressive behaviour of foams is an elastic response initially, a compaction stage with a plateau-like stress response (the densification, representing a large change in the material density due to a small change in the applied load/stress) and the after-compaction stage of deformation (e.g., a hardening plastic behaviour is considered to be relevant to a description of this stage). For example, such the representation at has been realised with the ELASTIC, CRUSHABLE FOAM, and CRUSHABLE FOAM HARDENING options of the ABAQUS software in paper [Rizov, 2005]. This paper modelled the indentation of a hard indentor tup into polymeric closed-cell foam.

An example of the code-embedded description of a honeycomb material is the MAT_HONEYCOMB material model from the material model database of the DYNA hydrocode outlined in manual [LS-DYNA Manual, 1999]. This model treats a material simulated in paper [Lopatnikov, 2004] as a homogeneous orthotropic material. Non-linearity of the material is taken into account (the stiffness modulii are dependent on the volumetric strain) but the strain-rate sensitivity is neglected and the input pressure-density curves for this material are taken from quasi-static experiments. It should be noted, however, that the paper [Lopatnikov, 2004] simulates high-velocity impact against metallic foam, for which problem strain rate is significant.

The same MAT_HONEYCOMB model is compared in paper [Hanssen, 2002b] with a number of other models from the DYNA material database [LS-DYNA Manual, 1999]. This set of models includes: i) a generalisation of the MAT_HONEYCOMB model that takes into account deviatoric strains under hardening (the original MAT_HONEYCOMB model considers only the volumetric strain as a parameter that affect the material hardening); ii) a MAT_CRUSHABLE_FOAM model [LS-DYNA Manual, 1999] that describes the material as an isotropic elasto-plastic solid at tension, an elastic material at unloading and a crushable material, which has a rigid-plastic response with zero Poisson ratio, at compression; and iii) a MAT_BILKHU/ DUBOIS_FOAM model [LS-DYNA Manual, 1999] that treats the yield limit in the von Mises fashion, which is located on an elliptic yield limit surface in the stress space. In all the models inspected in the paper [Hanssen, 2002b] the yield limit stress versus strain is an input curve. In addition, the MAT_BILKHU/DUBOIS_FOAM model requires the pressure-volumetric strain dependence as an input as well. These models are physically simple but they require a large number of input data. Calibration of the input parameters is not easy. Some of the parameters may have physical meanings and can be deduced from the material properties but others seem to be more of a 'fitting' nature (see [Reyes, 2004]). Thus, it might be possible to calibrate the input data against a given set of tests as in the paper [Hanssen, 2002b] but there is no guarantee at all that for another class of problems this calibration would work as well, if the input parameter data are rather indirectly associated with the mechanical properties of the material and with the parameters that affect the process from the 'non-calibrated' class of problems.

With the rather large size of cells for some foam and honeycomb materials, the micro-mechanical behaviour is not easily separable from the continuum behaviour (discussion on this topic can be found in paper [Broberg, 1997]). A micro-mechanical numerical approach has been realised in paper [Ruan, 2003] for modelling the behaviour of a hexagonal aluminium honeycomb with the ABAQUS code. Shell elements with elasto-plastic behaviour have been used for meshing the material; mechanisms of crushing have been analysed and the resistance curves and limit stress envelopes in the form of analytical relations have been derived. A similar approach has been used as the basis of the modelling conducted in paper [Chung, 2002b]. A representative volume (12x12 cells) was directly simulated with the ABAQUS software. Shell elements have been used for the cell walls of the polycarbonate foam considered experimentally in paper [Chung, 2002a]. Next, this volume was considered as an element of a periodical structure in order to simulate behaviour of a bulk volume. An elasto-plastic model for the shell elements has been employed and the bi-axial load tests have been described. It should be noted that the yield limit in this model was, obviously, a fitting parameter. However, when simulating the dynamic tests of the paper [Chung, 2002a], a rate sensitive model for simulation of the cell walls was used, increasing the number of fitting parameters. The stress strain response was described reasonably well. However, due to the microstructural nature of the description, it is not surprising that the time response during the material deformation has not been described well. Generation of a finite-element model (the computational mesh) can be a time-consuming exercise and specially designed mesh-generators for erecting honeycomb structures from 2D-shell elements are currently being introduced and used for the analysis of cellular materials with hydrocodes such as DYNA (see, e.g., [Nguyen, 2005]).

A constitutive model taking into account finite deformations is suggested in paper [Mohr, 2004] for the description of an aluminium foam material. A testing methodology for determination of parameters of the constitutive model is also suggested. The modelling results describe the compression static tests at complex stress states reasonably well. However, the rate sensitivity is not considered within this model and the peculiar elastic response of cellular material under tensile loading (including complex loading that may involve shear and tension) is also not incorporated in the model. Constitutive rate sensitive models are developed in papers [Merzhievsky, 1992a; Resnyansky, 2004b], which are applicable to isotropic materials. The structure of the materials can be taken into account phenomenologically and the current micro-parameters of components (the cell wall material and air) can be found from the micro-mechanical equations involved in the model. In the paper [Resnyansky, 2004b], the model has been verified for aluminium foams subject to high-velocity impact by flyer plates.

4.5 Target response during ballistic impact. Modelling of the response

A ballistic projectile brings a high energy, essentially exceeding the damage resistance of a target. Impact by a projectile frequently results in penetration of a target, which leads to the introduction of the ballistic limit velocity. This velocity (V50), which is a limit velocity for a given projectile and target, resulting in the 50% chance of penetration, is associated with the energy E_a absorbed by the target during the perforation. Links of V50 with E_a will be considered in detail in section 6. The present subsection reviews papers on the experimental and theoretical study of target behaviour during ballistic impact. Theoretical prediction is quite hard because of the numerical difficulties associated with large deformations and fracture of composites and cellular materials during ballistic impact. An impact is accompanied by energy absorption, so accuracy of the predication is closely related to the subsequent evaluation of factors associated with after-impact characteristics such as V50 and E_a.

Specifics of composite target response when subject to high velocity impact follow from the structural features of the composite. These material features usually include a high directional anisotropy and reinforcement. The reinforcement feature has been analysed in the past, while developing hybrid and layered structures. The design objective of such structures against the load from a compact source (such as a projectile) was to redistribute the load over a wide zone in order to reduce damage in an object being protected by front sacrificial plates. This principle has long been used in the space industry when using space-separated or sacrificial shields (bumpers, which are called Whipple shields) against meteoroid impact to shatter a projectile. For a compact projectile that keeps its integrity during impact, hybrid target arrangements are more suitable. For example, the benefits of a SiC front layer, which spreads the impact load before transmitting it to an aluminium main structure, are considered in paper [Gupta, 2002]. Modelling of impact against multilayer systems using the EPIC hydrocode has been conducted in paper [Robbins, 2004]. This numerical study analysed in detail the damage mechanisms and the spreading of the load. Factors, such as pre-damage of the brittle front layer and imperfections of the layer-target interface have been considered; it was found that the front layer pre-damage state is more significant than the interface's imperfections. A quite obvious conclusion was made that the front layer (with a high sound speed) spreads the load effectively.

The space between the composite sheets in a multi-layer sandwich foam-filled target is critical for the protective capacity of hybrid targets under hypervelocity impact [Akahoshi, 2001]. For the extreme conditions of hypervelocity impact, the hybrid materials used in several space-separated shields may take very exotic forms in order to reduce areal weight and to increase protective capacity against impact. For example, a double bumper shield described in paper [Tanaka, 2001] contains several sheets of Vectran polymer fibre composite (a Japan manufactured fabric with fibre tensile strength close to Kevlar and with close-to-zero moisture absorption capacity) that is sandwiched with aluminium and stainless steel meshes. This shield is capable of stopping a 1 g-mass 13 mm-diameter projectile that is launched at 7 km/s-velocity.

The study of fracture under high-velocity impact is very challenging because the evolution of internal material structure has to be traced. The in-situ response of a target is different at low and high-velocities of impact because, first of all, the material fracture response needs time for the fracture to occur. The time factor is critical under high-velocity impact, when a projectile penetrates faster than damage is accumulated at the rear side of a target. In turn, the damage accumulation process is associated with wave circulations through the target thickness and the reflection of the waves from the free rear surface (that normally causes spallation and, in general, severe tension). Comparison of the time that is necessary for the waves to circulate through the thickness of the target and for the damage to accumulate with the time that is necessary for penetration of the projectile provides the conditions for separation of a low-velocity impact regime from a high-velocity (ballistic) impact regime.

An interesting illustration (traced by high-speed photography) of the reinforcement effect has been observed in paper [Hammond, 2004] for the case of high-velocity impact by steel 12.7 mm-diameter balls against targets of approximately 2 mm in thickness, which are made of quasi-isotropic and unidirectional composites. The observations show a sequence of the fracture events during ball penetration. For the quasi-isotropic laminated composite, delamination of the composite laminas at the front surface of the target (this area is sized in 2-3 diameters of the projectile) develops after localised fracture near the projectile exit area at the rear side has occurred. For a unidirectional composite, the fracture at the front surface occurs along the whole length of target in the fibre direction, also referred to as 'generator strip' (see paper [Tan, 2005]). Another illustration of the reinforcement influence was published in paper [Fujii, 2002]. This paper has reported in-situ observations by means of high-speed photography of the rear surface of composite targets. The targets were made of CFRPs with fibres of different strength. Study of high-velocity impact against the targets has demonstrated a larger area of damage in the case of fibres with higher strength.

Other in-situ observations of a CFRP target penetration by steel balls in the range of impacts from 150 up 300 m/s have been reported in paper [Tanabe, 2003a]. This study has shown that i) within the lowest limit of the velocity range, buckling behaviour is observed, involving a large area of target in the damage process (the projectile-target interaction time is long enough for damage to be accumulated within a large target area and, thus, the energy is absorbed by a large area too); and ii) within the highest impact velocity range, a plugging behaviour is observed, so the damage is localised within a zone that is close to the area of contact with the projectile (the projectile reaches the target's rear surface faster than the damage has accumulated at the periphery of the target). In paper [Tanabe, 2003b], the authors of the same team studied the impact in a wider range of velocities (150-1300 m/s) against CFRP and carbon/ carbon targets which were instrumented with PVDF and constantan gauges. These observations showed the effects of structural modifications of a material (the fibre processing) on the stress level being developed in the target material during impact and resulting in fracture of the target. Generally, the observations indicated that, at a stress level which exceeds a certain limit (that depends on the target material), the damage mechanism switches to 'fluid-like'. This mechanism is actually the plugging mechanism, which typically occurs at impact velocities higher than 600 m/s, exceeding the Hugoniot elastic limit. In this regime the projectile-generated shock wave, propagating into the target, detaches from the projectile head. This damage mechanism prevails when the material strength can be neglected in the analysis of the impact response. The same team studied a carbon/carbon composite (a brittle material) within the ballistic range of impact velocities (from 600 up to 1500 m/s) (see [Fujii, 2003]). PVDF gauges for in-situ strain measurements and high-speed photography were employed for the observations reported in the paper [Fujii, 2003]. The experimental study, validated with AUTODYN simulations, demonstrated that different fracture mechanisms (crack propagation in the matrix or fibre fracture) are possible, depending on the relationship between the projectile velocity and the target thickness. It should be noted that, in a brittle material, the fracture might be caused either by compressive stress due to the pressure generated by a projectile or by tensile stress due to the rarefaction wave reflected from the rear surface of the target. Both deformation modes complemented with shear might be reasons for the selection of certain fracture mechanisms (on the damage modelling in a brittle material, see [Resnyansky, 2003]).

Modelling of target response to ballistic impact is very challenging. Even within the scope of conventional target materials, paper [Wilkins, 1978], which focuses on the numerical simulation of penetration and perforation processes with a hydrocode, stresses that modelling should concentrate on the understanding of physical processes in the experiments being interpreted. Review [Rajendran, 1997] states that nobody has yet developed a complete model in order to describe the penetration of composite material targets. Since the publication of that review, composite modelling has progressed significantly into the development of anisotropic models and models that take the composite microstructure into account. However, it seems that the conclusions of the review are still valid, specifically, for analysis of failure mechanisms when modelling penetration of composite targets by hard projectiles. Therefore, numerical analysis is presently used for interpreting isolated facts, associated with target response to ballistic impact, rather than to modelling of the whole phenomenon.

When a fluid-like mechanism of fracture prevails at high velocities of impact, the fibres fail immediately in the vicinity of the projectile-target contact area due to the extreme stresses being developed that exceed the strength of the composite. At more moderate velocities less than a critical velocity V_c (or against thicker targets for an intermediate velocity regime) when fibres do not all fail at once, the high stress area distributes over a wider area and the fibres are mainly transmitters of the load. In this case, fibre failure may occur only if the tensile stress in the fibres exceeds their strength. There is no plug formed in this case and the projectile penetrates through the opening, preserving contact with the target via the opening's edges. The target thus absorbs kinetic energy, and the projectile loses this energy due to friction. The effect of friction on the residual velocity has been studied numerically in paper [Lim, 2003] for the case of high-velocity impact against a Kevlar fabric target. It should be noted that the braking force dependence in the contact algorithm engaging the friction allows the authors, when necessary, to simulate the transition regime at $V_i=V_c$ but neither the modelling or the force dependence explains the physics of the process in the transition regime. The effect of friction has been considered in paper [Duan, 2005b] within a DYNA-hydrocode simulation of the ballistic impact against a Kevlar plain-woven fabric target. The friction effect has been confirmed, but a friction coefficient has been used as a fitting parameter. This modelling does not identify a possible change of the penetration regime at $V_i=V_c$, because all the calculations have been performed for velocities of impact $V_i>V_c$. Therefore, this study does not clarify the importance of the friction effect and the transition regime.

Nevertheless, several attempts at finite-element analysis and hydrocode modelling exist, which are designed to understand the phenomenon of composite response to impact as a whole. Paper [Chocron, 2001] has studied the impact of the armour-piercing 7.62 mm-projectile APM2 on the edge of a metallic target. The objective of this consideration was the development of a method that is able to fracture the projectile's core. The AUTODYN hydrocode was used for modelling. Analysis of the modelling results suggests that the core has to interact with the target in order to be fractured and the areal density should be not less than 2 g/cm^2. Paper [Mahfuz, 1997] describes the finite-element modelling of cubic samples in a rig that is associated with compression of an SHPB sandwich sample. Two directions of compression of a laminated composite (normal-to-the-layer and along-the-layer directions) are considered. Elastic modulii are related to modulii obtained from an SHPB test. As mentioned in Section 3, this relationship is questionable because the SHPB test is incapable of describing the elastic material characteristics. Mechanisms of damage are theoretically analysed, using the modelling results. A DYNA-hydrocode study of a hybrid composite-ceramic target conducted in paper [Mahfuz, 2000] has demonstrated that the in-plane and transverse stresses in the target reach a maximum at the impact velocity of a FSP (fragment simulating projectile) equal to V50.

Tests and simulations in the ballistic (plane impact tests) and hypervelocity (impact by aluminium spheres) range of impact velocities of projectiles against a Kevlar/epoxy fabric target have been conducted in paper [Hayhurst, 2001] (the model reported in paper [Clegg, 1999] was used for the AUTODYN modelling). VISAR velocity traces of the rear surface of the composite targets show the importance of deformational anisotropy of the composite, which should be taken into account. Therefore, rather substantial parameter manipulation of the Mie-Gruneisen equation of state that is used by the model has been required. The VISAR traces indicate two regimes of the rear surface acceleration, which are a preliminary response due to the stress longitudinal pulse (precursor) and a main pulse due to the compression (plastic) wave.

4.6 Oblique impact. Non-ideal impact

In reality, a projectile-target encounter normally occurs at some angle of incidence, yaw, or when the target is moving. Therefore, impact is almost certainly non-ideal. In many cases the non-ideality can be ignored, but in some cases it cannot be ignored because it contributes to the target response. A relatively large number of papers have studied the oblique impact that may result in more serious consequences to a target than normal impact. For example, a study conducted in paper [Butcher, 1979] on LVI (low-velocity impact) testing of CFRP samples concluded that oblique impact has more serious damaging effects on unstressed sample than normal impact.

The non-ideal conditions occurring on ballistic impact significantly affect the mechanisms of failure in the target material. Paper [Ambur, 2001] considers the fragment threat due to turbine engine failure, on an aircraft structure. The influence of the pitch, yaw and roll of cubically shaped fragments on the character of damage in the target has been evaluated, using DYNA3D-modelling. Gas gun tests, that maintain the projectile orientation at impact, were conducted. The experiments and modelling showed that impact events at roll and pitch angles of the order of 5° result in a change of the perforation failure mechanism between plugging and petalling. The generation of cracks associated with a change of the failure mechanism and an increase in the perforation hole were also observed. Paper [Cunniff, 1999] analyses the ballistic performance of Kevlar armour systems. This study has demonstrated that at certain areal densities, an advanced perforation mechanism is initiated at obliquity angles near 30 degrees. In this case a cylindrical projectile diverted significantly from the straight path after the start of perforation and the impact initiated cross strains in the in-plane and cross yarns of the target's textile, which reduced the ballistic performance within this range of angles. Paper [Finnegan, 1993] acquired the ballistic limit velocity for steel and aluminium targets (target thickness approximately 1.5 mm) that were impacted by steel projectiles (typically balls) at velocities from 0.5 up to 1.5 km/s. A study of projectile breakage at high obliquity angles (near the ricochet regime) has been conducted and a change of the fracture mechanism of the target material from plugging to petalling was observed.

Oblique impact against a hybrid target (ceramic plate backed by an armour plate) was considered in paper [Zaera, 1998]. The target was impacted by 7.62 mm and 20-30 mm projectiles at normal and oblique angles of encounter. An analytical model for derivation of the residual velocities and masses of the projectiles after penetration of the sandwich target was suggested in this paper. The ballistic equivalency rule was used, with which the actual target thickness h_t is substituted by an equivalent thickness h_t':

$$h_t' = h_t / \cos(\theta) \quad , \qquad (2)$$

where θ is the obliquity angle (from the normal at the target surface to the projectile flight direction). The residual mass was in disagreement with the experimental results, so the Alekseevski-Tate equation (that is common in the penetration theory of long rods) was employed and a new equivalent distance for integration from the impact point to the edge point of the fracture area in the ceramic plate was introduced. These modifications rectified the model and allowed the authors to describe the experiments reasonably well. A similar study was reported in paper [Benloulo, 1998] for ceramic-composite targets penetrated normally by a 20mm tungsten projectile.

DYNA simulation of normal and oblique impact (30° obliquity angle) against lightweight armour (ceramic tile backed by composite plate) was considered in paper [Fawaz, 2004]. A decrease in ceramic-composite interfacial stress at oblique impact (when compared with the normal impact) has been observed for the 314 m/s-velocity of impact by a 7.62 mm AP projectile. Perhaps, this is a quite obvious result, because the normal component of momentum is less for the case of oblique impact than for the case of normal impact with the same absolute velocity. Therefore, the direct comparison of the interfacial stresses in these cases is not very fruitful. Similar to the result of the paper [Cunniff, 1999], a diversion of the projectile path from the straight line is observed in the study [Fawaz, 2004], which results in an elliptically shaped cavity.

Hydrocode DYNA-modelling of normal and oblique impact against CFRP targets, using an advanced rate-sensitive model [Resnyansky, 1997a] for description of the dynamics of laminated composite materials, has been reported in paper [Resnyansky, 2002c]; the modelling results have been verified with experimental tests. The calculation involved a projectile with an armour piercing shape (the projectile is considered to be deformable) impacting carbon-epoxy quasi-isotropic samples. The calculation results have demonstrated the reasons (which are substantiated by an analysis of shock wave circulation through the target thickness), why rule (2) may not be applicable to composite targets. For brittle targets with a moderate thickness, the obliquity angle factor is diminished at high velocities of impact. In this case, the failure mechanism (that is 'fluid-like', according to the terminology of the paper [Tanabe, 2003b] introduced in the preceding subsection) is determined by shock processes regulated by wave circulation in the normal direction through the target thickness (i.e., in this case, the failure mechanism is only slightly related to the projectile path in the target, when this factor should be dominating in order to apply the formula (2)).

A wide range of cases of non-ideal impact are considered in a recent review [Goldsmith, 1999]. This review covered the literature related to moving targets, oblique impact, and, generally, the non-ideal behaviour of projectiles during an encounter with a target (rotation, yaw, tumbling). Significant attention was paid to the results of numerical simulation. However, a very large portion of the review was devoted to long rod impact/penetration. For example, yawed impact is considered mostly for the case of long rod projectiles. Many examples, which can be found in the review, are results of the numerical simulation of non-ideal impact events. The empirical relations described in the review did not evolve significantly from the well-known long-rod penetration relations. The majority of the target materials considered in the review are conventional materials (metals, concrete and sometimes soil/sand).

The majority of the ballistic tests have been conducted with stationary targets. However, a strong factor, which affects the damage mechanisms in targets during impact, is target motion (see, e.g., [Hou, 1994; Wu, 1990]). Targets, especially air platform targets, are almost certainly moving. Paper [Wu, 1990] describes ballistic tests on the impact of blunt-ended projectiles against aluminium and steel moving targets (the target thickness is from 0.7 to 1.6 mm). The relative velocity of target movement is 40 m/s. The tests conducted in the paper [Wu, 1990] found an increase in the ballistic limit velocity by 24-29%. On the other side, the fracture mechanism is more absorbing, when compared with impact against a stationary target. Plugging (which is the only mechanism for the stationary target case) is complemented with petalling, a larger elliptical opening was observed for the moving target case and an accompanying crack attached to the opening was reported, which is absent in the stationary target. Significant deviations of the exited projectile from the line of fire (up to 60° at velocities slightly larger than V50) were observed with a large tumbling velocity after penetration. These tests, including impact by a conically nosed projectile, were modelled with the DYNA3D hydrocode in paper [Hou, 1994].

The majority of the ballistic tests published in the literature deal with inert projectiles. The effect of an explosive shell was assessed in paper [Anderson Jr., 1999a] that reports the modelling results of the effect of a high-explosive incendiary (HEI) projectile. The explosive projectile considered in the paper [Anderson Jr., 1999a] is a 23 mm HEI of type ZU-23 HE/I/T. The projectile's effect is simulated with CTH hydrocode. A test of penetration of a water tank, which is equipped with gauges inside the tank, is used for the validation. From the comparison between the numerical and experimental results it was concluded that the HEI projectile is initiated at 200 μs after the impact. The effect of a 23 mm HEI threat against the tailboom of a helicopter structure, which is loaded with forces comparable to typical forces developed in the RAH-66 Comanche helicopter, has been studied in papers [Caravasos, 1998; Orlino, 1995b]. The projectile encountered the target at normal incidence and its fuse initiated inside the tailboom. Extensive delaminations were observed, which are associated with overpressure due to the projectile's explosive initiation. The bending stiffness of the structure was estimated to be reduced by 45% after the event.

Numerical simulation of fire suppression in a dry bay neighbouring a fuel tank, which is subject to a HEI threat, has been conducted in paper [Crawford, 1994] using the SLAMII software. The number of fragments produced by the HEI munition after the fuse initiation was selected randomly from a Poisson distribution. The fragments' paths were determined by the deflection angle and the direction angle of the HEI projectile. These angles were randomly taken from a normal and uniform distribution, respectively. The SLAMII software is a representative of vulnerability software. In this study [Crawford, 1994], the software allowed the authors to evaluate the chances to suppress fire, depending on the fuel tank level, airflow, ventilation in the dry bay, and some other parameters. Altitude appeared to be a critical parameter. The effects of the blast/fragmentation due to HEI effects have been considered in paper [Huyett, 1995] where a HEI blast/fragmentation threat was applied to advanced transparent polymer laminated barriers. After comparison of the integral effect of 23 mm HEI ordnance with a number of FSPs (fragment-simulating projectiles) of different calibres, 12.7-mm fragment-simulating projectiles were selected for the study. Dissimilar polymers were used in the layer target in order to activate target synergism. It should, however, be noted that any blast effect cannot be reproduced properly with FSP impact.

Paper [Lewin, 1997] describes the modelling results of explosive shell detonation inside the fluid part (fuel) of a wing structure section. The DYNA hydrocode was used for the modelling and a 40-50 g charge of high explosive was selected as a loading method. The pressure peak recorded in the fluid was used for model validation. Survivability of the structure was assessed from calculation results by analysis of the damage character. No post-failure calculations and studies were conducted. The composite wing skin was simulated using the isotropic elasto-plastic material model from the DYNA material model database. The DYNA erosion option, which controls damage with the failure strain (obviously, a fitting parameter in this study), was used as a damage mechanism in the calculations [Lewin, 1997].

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19. ABSTRACT

The present review aims at a provision of scientific support to the introduction of the Tiger ARH (Armed Reconnaissance Helicopter) into service. The review examines more than five hundred recent publications on the impact response of composite and cellular materials which are constituents of modern air platforms, specifically, helicopters. Using the ARH in an operational environment makes ballistic damage assessment an important issue. This review focuses on the factors of material response associated with structure vulnerability, such as damage resistance and damage tolerance.

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